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# Steel manufacturing clusters in a hydrogen economy – Simulation of changes in location and vertical integration of steel production in Northwestern Europe

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ABSTRACT

With the move to a hydrogen-based primary steel production envisioned for the near future in Europe, existing regional industrial clusters loose major assets. Such a restructuring of industries may result in a new geographical distribution of the steel industry and also to another quality of vertical integration at sites. Both implications could turn out as drivers or barriers to invest in new technologies and are thus important in respect to vertical integration of sites and to regional policy. This paper describes an approach to model production stock invest for the steel industries in North-Western Europe. Current spatial structures are reproduced with capacity, technical and energy efficiency data on the level of single facilities like blast furnaces. With the model developed both investments in specific technologies and at specific production sites can be modelled. The model is used to simulate different possible future scenarios. The case with a clear move to hydrogen-based production is compared to a reference scenario without technological shift. The scenarios show that existing trends like movement of production to the coast may be accelerated by the new technology but that sites in the hinterland can also adapt to a hydrogen economy. Possible effects of business cycles or a circular economy on regional value chains are explored with a Monte-Carlo analysis.

## 1. Introduction

Achieving a climate neutral economy by 2050 or earlier is the target of certain national governments and the EU Commission. Several studies have provided evidence of such an economy being technically feasible. However, in a multi-level political system like the EU, its actual implementation requires the involvement, expertise and commitment of (sub-)national political entities and stakeholders (e.g., companies). Heavy industry in general, and the steel industry in particular, face specific technological and economic challenges in this process (Davis et al., 2018). In their broad analysis of several heavy industries, Bataille et al. (2018) differentiate between three main technical strategies to achieve climate neutrality: (1) the use of sustainable biomass; (2) carbon capture and storage (CCS); and (3) the use of renewable electricity. These three technical strategies are complemented by energy and material efficiency strategies to reduce steel use and to increase secondary production aiming at a more circular economy. While these measures save energy and resources and are often economic they cannot enable a climate neutral steel production alone.

As global *sustainable biomass* potential is significantly limited and heavy industry would have to compete for the limited available resources with the transport sector, this strategy is deemed by most studies to be only part of the solution and may only become a reality in regions with high potential for biomass production, such as Scandinavia or Canada. Nwachukwu et al. (2021) demonstrate that the use of forestry biomass could contribute to a 43% reduction in GHG emissions of the Swedish steel industry. Many scenarios assess *CCS*, the second strategy, to be the most effective and important solution for “decarbonising” heavy industry. The IEA’s (2020) “Iron and Steel Technology Roadmap” still foresees an important future role for CCS in their global “sustainable development scenario”. However, public acceptance of this approach is fragile. In a case study on the Port Talbot steelworks in the UK, Williams et al. (2021) found out that the adoption of CCS was seen critically by at least parts of the public. Furthermore, with the political shift from the

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*Abbreviations:* BF, blast furnace; BOF, basic oxygen furnace; CS, crude steel; CCS, carbon capture and storage; DRI, direct reduced iron; EAF, electric arc furnace; ETS, European Union Emissions Trading System; HR, hot rolling; NWE, Northwestern Europe.

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target of a *low carbon society* to *climate neutrality,* the CCS solution has become less attractive as the $CO_2$ capture rates are typically below 100%. The third strategy has gained increasing levels of attention in recent years and the *electrification* of heavy industry has found its way into scenario analyses (e.g., Lechtenböhmer et al., 2016; Ruhnau et al., 2019; Material Economics, 2019) as well as into industry roadmaps (Eurofer, 2019; IEA, 2020). Studies show there is the potential to generate renewable electricity in large quantities and at reasonable cost around the world (Fasihi et al., 2016; Ram et al., 2018, Fasihi and Breyer, 2020). Fischedick et al. (2014), Hölling et al. (2017), Vogl et al. (2018) and Bashkar et al. (2020) analysed energy needs and costs of the direct reduction route with the use of hydrogen as an indirect electrification option for primary steel making. The analysis reveals significant extra costs compared to today's predominant blast furnace route but also showed that the new route could be economically viable in the future under certain assumptions about future hydrogen costs and $CO_2$ prices. In their recent meta-analysis of technical research on hydrogen-based steelmaking Li et al. (2021) conclude that hydrogen steel making is technically feasible, but that there are still options for further optimisation of the processes that could further drive down the costs of this route. Following the announced plans of European steel producers to transform their plants to the new technology the analysis of technical concepts has been complemented by case studies on the ability of the technological innovation system (TIS) to adopt such a strategy (Kushnir et al., 2020) and on the macroeconomic effects (Mayer et al., 2019). A first analysis about competitiveness of different world regions in regard to hydrogen based steel making has been provided by Gielen et al. (2020) who showed that there are economic opportunities for countries like Australia to produce climate neutral steel products for the world market in the future.

While research has been undertaken into technical and economic feasibility, the sociotechnical system and the overall economy, there is a lack of analysis on how such a transformation would impact on the competitiveness of specific steel sites and the spatial structure of European industry. Such analyses are crucial for at least two reasons. First, in Western Europe, several regions are now developing energy strategies for climate neutrality and (more recently) specific hydrogen strategies or roadmaps. At all these levels of policymaking there is the need for a consistent analysis of future regional infrastructure requirements to inform the debate between policymakers, companies, trade unions and society as a whole. Future infrastructure needs depend on the location of future industrial demand, while access to infrastructure is an enabler for industrial relocation. However, existing models and scenarios analysing technology transformation within the steel industry are not explicit in terms of sub-regions or even sites (e.g., Morfeldt et al., 2015; Material Economics, 2018; van Ruijven et al., 2016; Arens and Worrel, 2014; Wörtler et al., 2013). They present the results on an aggregate level only (for a world region like the EU or a specific country) and the scenario literature available does not analyse the specific impacts of industry transformation on the competitiveness of certain sites or smaller regions under a regime aiming for climate neutral production. The second reason why analysis of the locational effects of industry is crucial is to inform regional policies.

The aim of this study is to analyse how the geographical distribution of steel production could be affected by decarbonisation, involving the strategy of indirect electrification via hydrogen. It analyses the relative changes in competitiveness of sites within the region of Northwestern Europe (NWE) brought about by the transition to a hydrogen economy. The region analysed includes France, Benelux (Belgium, Netherlands and Luxembourg) and Germany. A spatial investment model for the steel industries in Northwestern Europe was developed and applied for the purposes of the analysis. In the model, current spatial structures are reproduced by capacity, technology and energy efficiency data at the level of single facilities (e.g., blast furnaces). Based on this approach, future investments in specific technologies and in production sites are modelled and the evolution of future regional production structures under different market conditions is explored in various scenarios. A Monte Carlo analysis is used to test the robustness of the scenario results. The analysis aims to better understand what spatial trends might occur from integrating the steel industry into a hydrogen economy and how regions and their actors in densely industrialised Northwestern Europe could prepare for such a development. The results of this paper aim to improve understanding at national and EU level of the strengths and weaknesses of specific regions in order to support stakeholder interaction. The paper is organised as follows: Section 2 covers the background and methods, Section 3 presents the modelling results, Section 4 discusses the results and points to possible future avenues of research whereas in Section 5 the conclusions are presented.

## 2. Background and methods

This section describes relevant features of the techno-economic system of steel production and its representation by a quantitative model illustrating the relevant inter-relations between selected parts of the system. As a starting point, technological and geographical *background* material and data about the steel production system in Northwestern Europe is presented to clearly define the system boundaries. Subsequently, the methodology for deriving the quantitative scenarios is outlined, consisting of a brief description of the model and the presentation of the key assumptions used to define the scenarios.

### 2.1. System background

#### 2.1.1. Presentation of relevant technologies and integration

Three main drivers of site location are identified that shape the geographical analysis in the following section and the model structure described in section 2.2: The first one is existing assets, a second one is transportation costs for the raw materials and the third one is financial benefits by vertical integration (heat and gas integration). The analysis shows that moving from today's predominant coal-based route to a hydrogen-based route changes the potential for the reuse of existing assets and financial integration benefits and thus transport costs are likely to gain in importance at the expense of the value of existing assets, which are today the main driver for location.

Although there is a global market for steel products, the production of steel tends to be organised in regional systems where the subsequent steps of the production and value chains are geographically close to each other. Economically attractive iron ore and coking coal deposits are concentrated in a few locations around the globe and these resources are transported all over the world to steel manufacturing sites close to the markets for steel products, such as civil engineering or the automotive industry. This is because transport costs for the granular bulk materials of iron ore and coal are very low compared to the non-granular finished or semi-finished steel products in the form of slabs or coils.

The focus of this study is to analyse the introduction of hydrogen-fuelled shaft furnaces to produce direct reduced iron (DRI) plants. This kind of route is referred to as H-DR. Although it is to be phased out, the standard coal-based primary steel production route including a blast furnace and a basic oxygen furnace (BF-BOF) and associated features are still shown in the model. This is because until 2040 there will be a transition period during which some of the BF-BOF route's assets will remain, providing specific integration advantages for hot rolling compared to H-DR. Fig. 1 shows the production chains for both conventional and decarbonised steel. The top of the figure shows the BF-BOF route and illustrates the various integration benefits it offers. As the basic oxygen furnace requires liquid iron as a feed, these two aggregates are usually located close to each other (typically on the same site) to minimise energy losses. Coking and sintering are, in most cases, also integrated at one site. One reason for integrating hot rolling into steel production is that BF/BOF sites provide low cost fuel, because gases are produced as a by-product of the processes. These gases have an exceptionally low energy content in relation to their volume;

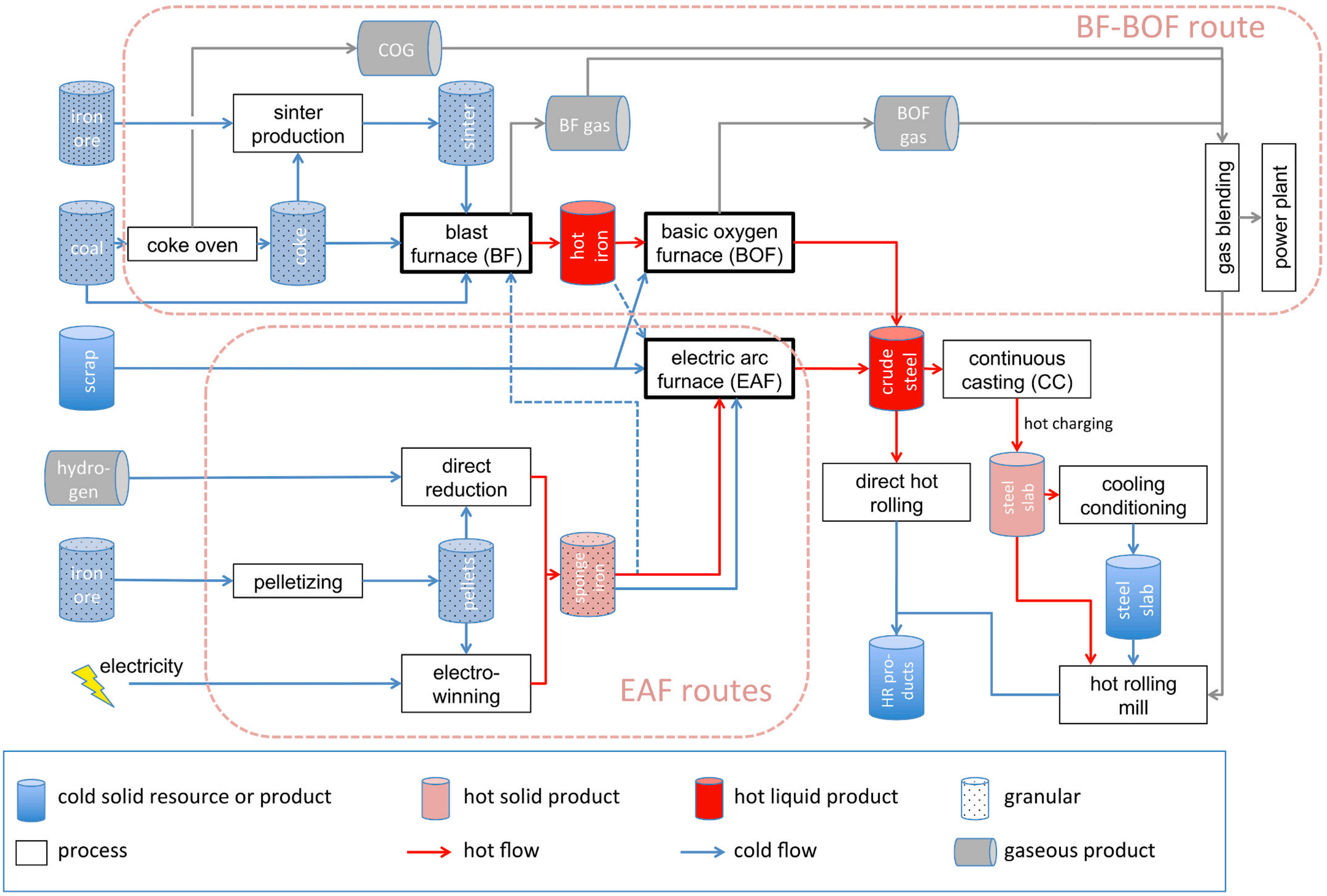

**Fig. 1.** Main resource and product flows in selected routes of crude steel production and hot rolling [source: own figure].

consequently they can only be stored for short periods of time. Using these gases to reheat furnaces in the hot rolling mills provides a continuous "sink" and the need for storage can thus be minimised. When firing reheating furnaces with BF and/or BOF gas, almost all the energy content is converted into useful energy. An alternative use for BF/BOF gas is to fire gas power plants, but BF/BOF gas power plants cannot be operated according to supply and demand in the electricity market. As a result, they are exposed to increased market pressure. Therefore, "*gas integration*" is also used as a cost criterion in the model.

Below the BF-BOF route in Fig. 1, other routes involving electric arc furnaces (EAF) are illustrated. In most cases electric arc furnaces are used today to recycle steel scrap, but at certain sites around the world they also process DRI, meaning they can also be part of a primary route. Mixed feed of scrap and DRI is common. Hydrogen offers a future carbon-free option for reducing iron ore, whereas current DRI plants use natural gas.

Another relevant criterion is *heat integration*: Both the basic oxygen furnace and the electric arc furnace produce liquid crude steel, which is cast in the form of slabs, typically in a continuous casting (CC) process. Further integration at a site, involving the subsequent step of hot rolling (HR), often takes place. The option of "hot charging" can be beneficial, as this offers energy savings; however, it requires coordinated production. The most energy-efficient hot rolling process is "direct rolling".

### *2.1.2. Geographical scope and characteristics of the steel industry in Northwestern Europe*

The following geographical analysis justifies the geographical boundaries and develops an analytical framework for the categorisation of existing sites according to their *existing assets* (including *vertical integration*) and their access to *transport infrastructure*.

The geographical scope of the analysis is Northwestern Europe. The five countries included all have substantial steel trade (see. Table 1). The region is fairly homogenous and has been a common steel market since the foundation of the European Coal and Steel Community (ECSC) in 1951 (together with Italy). In 2015, 55% of all steel imports (in total 48 Mt/a) in the five countries were connected to the four other countries in the group. Important intra-NWE trade relations comprise exports from Belgium to France and Germany, from France to Germany and Belgium, and from the Netherlands to Germany. 45% of all exports (in total 61 Mt/a) are within Northwestern Europe; this is lower than the import share due to the fact that the group as a whole is a net exporter of steel products, with net exports amounting to 12 Mt/a.

The regional markets of course overlap: France trades with Spain and Italy, which are subsumed together with all the other EU-27[1] non-NWE countries and the UK under the category "other EU-27+UK". Another example is Germany, which delivers around 50% of its steel exports to "other EU" countries, particularly to Austria, Italy and Poland. In addition, all five Northwestern Europe countries (especially the Netherlands) have strong trade relations with the UK (no longer a member of the EU).

The production sites are differentiated between two key categories, (i) access to transport infrastructures and (ii) degree of vertical

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[1] The EU-27+UK referred to in this context comprises of today's EU-27 and the UK as a former EU member (until 2020).

**Table 1**
Trade balance of finished steel products in million tonnes for NWE countries in 2015 [Eurostat PRODCOM database, own analysis].

| | | Recipient | | | | | | | Total exports | NWE share | EU-27+UK share |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | BE | FR | DE | LUX | NL | Other EU | Non-EU | | | |
| **Exporter** | Belgium (BE) | – | 3.7 | 4.6 | 0.2 | 1.8 | 2.8 | 1.8 | 14.9 | 69% | 88% |
| | France (FR) | 2.1 | – | 2.7 | 0.6 | 0.3 | 4.6 | 2.3 | 12.5 | 45% | 82% |
| | Germany (DE) | 1.2 | 1.9 | – | 0.2 | 2.0 | 10.5 | 4.6 | 20.5 | 26% | 78% |
| | Luxembourg (LUX) | 0.2 | 0.2 | 0.5 | – | 0.2 | 0.6 | 1.7 | 3.4 | 33% | 51% |
| | Netherlands (NL) | 1.2 | 0.8 | 3.1 | 0.0 | – | 2.7 | 1.7 | 9.5 | 53% | 83% |
| | Other EU-27+UK | 1.4 | 3.7 | 8.7 | 0.0 | 1.2 | – | – | – | – | – |
| | Non-EU | 3.3 | 0.3 | 1.6 | 0.0 | 0.7 | – | – | – | – | – |
| **Total imports** | | 9.3 | 10.7 | 21.1 | 1.1 | 6.2 | – | – | – | – | – |
| **NWE share** | | 50% | 62% | 52% | 96% | 69% | – | – | – | – | – |
| **EU-27+UK share** | | 65% | 97% | 93% | 100% | 89% | – | – | – | – | – |

integration". The access to *transport infrastructure* shapes the transportation costs.[2] This is a particularly relevant analytical category in the economic assessment described in this paper; consequently, the sites are differentiated between: (1) "coast"; (2) "wet inland"; and (3) "railway inland" sites.

A second site category is *vertical integration*, where the differentiation is between: (1) isolated crude steel making; (2) isolated hot rolling sites; and (3) vertical integrated sites.[3]

The steel industry in the NWE countries was analysed in depth to record the relevant stocks: i.e., primary and secondary steel making capacities as well as different types of hot rolling mills.[4] The map in Fig. 2 shows all the analysed sites, rated according to the two categories. The combination of the two categories with the three specifications results in nine possible specifications (although one combination did not in fact exist). The magnitude of the site icons on the map indicates their respective capacity (in tonnes of product per annum).[5] An overview of the existing stock and its overall capacity use is given in the supplementary material.

Table 2 compares a sample of typical sites in terms of their respective infrastructures and cost structures. The analysis of the production stock indicated at the left-hand side of the table shows that the sample includes integrated sites with steel making and hot rolling, Florange as an example of a non-integrated site and the Charleroi sites as partly-integrated sites. The middle columns of the table show the transport infrastructure. Most of the steel making sites are "wet", i.e., they have their own seaport, or a port at a river or canal. However, in serving the hinterland, rail transport has replaced inland vessels in many cases because the shipping of bulk material on canals currently costs more than rail transportation. Former "wet" sites, such as Dillingen and Eisenhüttenstadt, are now supplied by the heaviest freight trains on the German railway network. Block trains run directly from the great seaports of Rotterdam and Hamburg to the sites. The service options at seaports also differ: the Rotterdam hinterland benefits from the recently introduced Valemax ship class, which can call at Rotterdam only – a specific advantage for the German sites at Duisburg and Dillingen. Valemax iron ore shipping to Rotterdam with transhipment and short sea transport to Bremen and Ghent (and temporarily to Dunkirk) has crowded out direct shipping from Brazil to the smaller ports.

The column at the right-hand side of the table shows the specific total transport costs for transporting one tonne of iron ore to the site. The lowest freight rates are to the steel sites with ports, such as Ijmuiden and Hamburg. The Duisburg sites are unrivalled inland sites in terms of transportation costs because the River Rhine can accommodate extra-large push tows consisting of up to six unit. Sites further in the hinterland, such as Eisenhüttenstadt and Dillingen, bear the highest transportation costs.

### 2.2. *Model description*[6]

The model developed optimises the geographical structure of the steel industry based on the total cost of the steel system taking into account (re-)investment and transport costs. It uses a linear optimisation procedure. Investment in iron reduction technology, crude steel making capacities and hot rolling mills are simultaneously optimised stepwise for each five-year period between 2015 and 2050, which means that investment decisions of prior periods are always reflected. The model assumes rational economic investments, perfect information and is actor-independent; the latter means it does not consider the strategic behaviour or special agendas of single actors, agents or companies.[7] A special feature of the model compared to other models using optimisation is the *lack of perfect foresight*.[8] The simplifying assumption is that all investing parties share the same expectations about the future development of demand in their markets for steel products, which is derived for every five-year period $t_n$ within the time horizon of the scenarios by trend-extrapolation from the "historical" development until $t_n$. Fig. 3 gives a simplified representation on the simulation of the investment decision in one period for two prototypical sites A and B.

Second to geographical driving factors, such as transportation costs, the most relevant triggers influencing investment decisions relate to existing assets, which are calculated for every site and every five-year period. These are:

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[2] Historically, the geographical structure of steel making in Continental Europe was shaped by transport costs and plants were erected nearby the coal mines. Today there are no more coal or iron ore mines in the region and the materials are imported from overseas.

[3] Integrated sites are defined for this purpose as sites where the maximum capacity for crude steel making and hot rolling does not differ by more than 100% from the minimum of both values.

[4] As a data source Wuppertal Institute's WISEE database on European industrial production stock was used. Seven different hot rolling plant types were identified (coil, plate, structures, wire rod, bars, railway track and seamless tubes).

[5] Crude steel and hot rolling capacities were not simply added together; the combined maximum was taken as an indicator.

[6] This section gives a brief description of the model developed. Further parameters used in the target function of the optimisation can be found in the supplementary material (Table 1). Some are discussed below in the sensitivity section

[7] This model simplification is due to the long term scenario horizon, where geographical factors (i.e., access to infrastructure) together with existing assets are likely to be the dominant drivers.

[8] Investments are optimised based on the expectation of „the market" about future steel demand, which is derived as a trend extrapolation from the respective previous time periods. In particular in the runs of the Monte Carlo analysis expectations about the future and the actual later development may differ significantly.

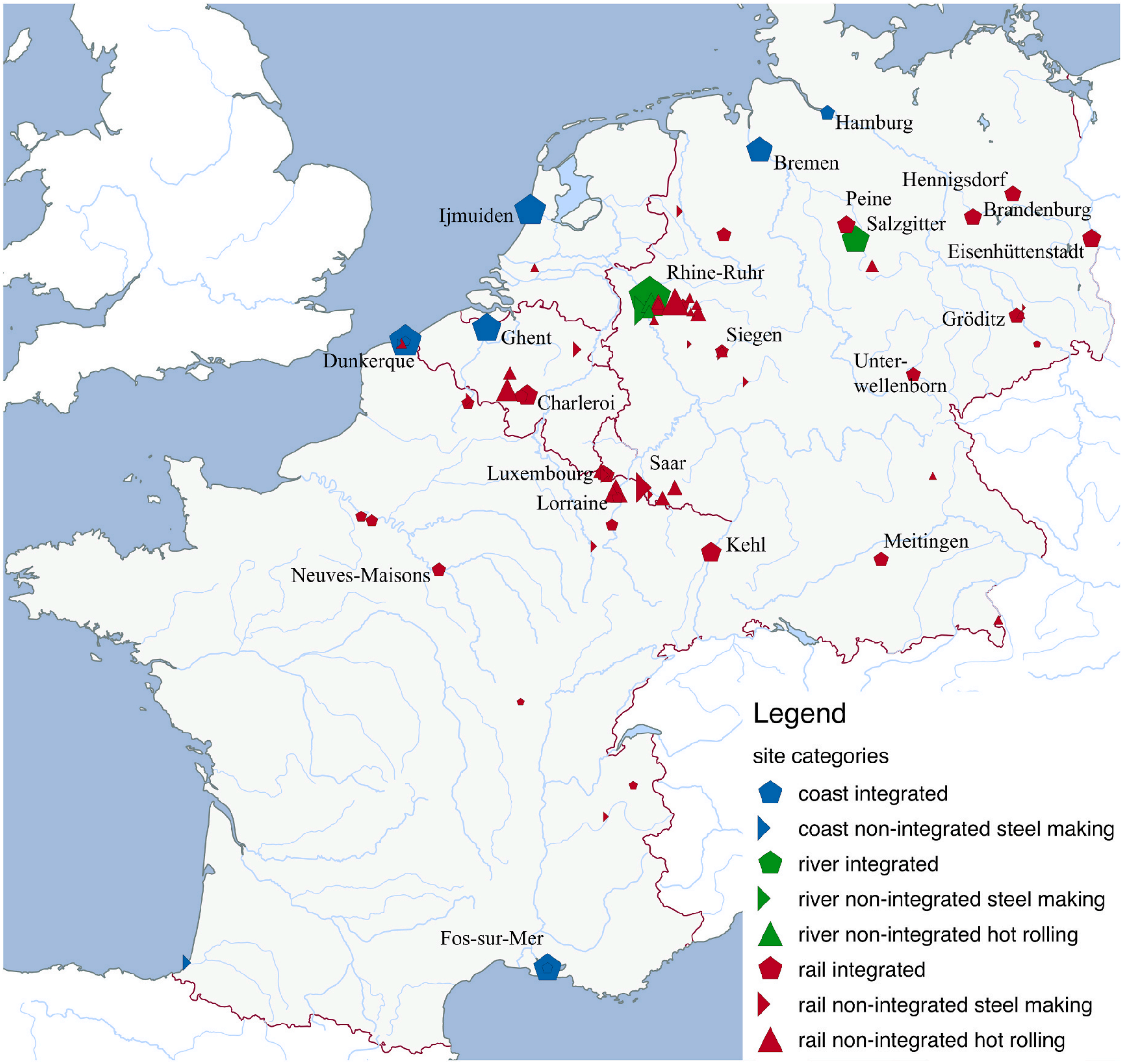

**Fig. 2.** Steel making and processing site types in Northwestern Europe [source: own map].

- the volume of "free" capacities having just reached the end of their technical lifetime that may be *retrofitted;* and
- the volume of "free" (i.e., not yet vertically integrated) capacities available for additional integration of steel making and hot rolling at a site (by adding hot rolling or steel making capacities respectively and realising financial integration benefits).[9]

Two additional criteria (not shown in the figure) are:

- the volume of "free" capacities that can deliver or use blast furnace gas or basic oxygen furnace gas (both of which are cheaper than natural gas); and
- the volume of disposable "free" periphery stock from the blast furnace route (i.e., coke ovens, sinter plants and basic oxygen furnaces[10]), as a criterion for investment in blast furnaces.

*Retrofit potentials* occur at a site when a plant reaches the end of its technical lifetime. It is assumed that the retrofit potential ends five years after the end of a site's lifetime. Later investments in the same kind of stock at such a site are rated as greenfield investments, with respectively higher investment costs.

Another criterion is the transportation costs of bulk materials and the loading costs for intermediate products, both of which are influenced by geography and infrastructure. Seaports generally have the lowest transportation costs, with sites served by trucks bearing the highest costs for bulk materials like coal and iron ore.

Expected future income flows, such as savings from BF gas use or costs (such as transportation costs), are rated by their net present value at the time of investing. Due to the linearity of the chosen optimisation function, it was impossible to take minimum/maximum capacities or

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[9] It was assumed that the integration of secondary steel making with the hot rolling of coils has no specific benefit as the quality requirements for coils are high compared to other steel products (see Daehn et al., 2017). The secondary route is, therefore, generally used for the hot rolling of other products; in particular, bars, structures and plates.

[10] Logistics infrastructure – especially for storing and shipping goods – as an additional periphery stock is also relevant in practice. Existing ore handling capacities are included in the model by assuming a financial benefit.

**Table 2**
Selected primary steel making sites with transportation links and specific transportation costs [source: authors' enquiries, costs for inland transport derived from BVU/TNS (2014) and Intraplan/planco/TUBS (2015).

| | Iron & steel cluster | Production stock | | | | | Seaport | Transport to seaport | Transport seaport – inland | | Specific transport costs (EUR$_{2012}$/t) iron ore (incl. sea transport) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Coke oven | BF/BOF (DRI) | EAF | HR sheet mill | Other HR | | carrier | Carrier (to inland sites) | Maximum load per transport (1000 tonnes) | |
| **Duisburg** | Rhine-Ruhr | X | X | | X | X | Rotterdam | Valemax bulk carrier | vessel (push tow, 6 units) | 16.8 | 10.98 |
| **Dillingen** | Saar | X | X | | | | | | rail | 3.8 | 14.78 |
| **Salzgitter** | | X | X | | X | | Hamburg | Cape Size bulk carrier | rail | 5.0 | 13.61 |
| **Eisenhüttenstadt** | – | | X | | X | | | | rail | 5.0 | 14.67 |
| **Hamburg** | – | | (X) | X | | X | | | – | | 9.38 |
| **Ijmuiden** | – | X | X | | X | | Ijmuiden | | – | | 7.65 |
| **Florange** | Lorraine | | | | X | | Antwerp | | rail | 3.8 | 12.23 |
| **Charleroi** | Charleroi | | | X | X | X | | | rail | 3.8 | 11.18 |

economies of scale into account. This is particularly imprecise when calculating blast furnace capacities, where economies of scale are important. However, the modelling results presented later in the paper show that this is not a decisive factor in the scenarios because the existing blast furnace capacities represent a strong asset and, therefore, dominate future markets in the simulation results.

### 2.3. Scenario definition

All scenarios and sensitivities analysed and presented in the results section share certain common assumptions and deviate in some specifications, as shown in Table 3.

The default case projection for finished steel production foresees stable production in relation to the mean production observed in the years 2018–2020 (this is a conservative picture that takes into account the two weak years in the steel market (2019 and 2020)). This default case was combined with *two technology pathways*: (1) a business-as-usual path (blast furnace route); and (2) a rapid adoption of new electricity-based primary steel production technologies (H-DR). The first combination is referred to as the "***reference base scenario***" and the latter combination as the "***electrification base scenario***" (see Table 3).

The choice of technology is made by assumption in the scenario, justified by price development (via the ETS) or regulatory policies (e.g., by the definition of best available technology). The model does not determine the choice of technology; it covers the spatial allocation of investment within the defined pathways.

Both base scenarios assume an increase of scrap availability by 1.6% p.a. Scrap availability is defined here as the availability of useable scrap (i.e., scrap that meets the quality requirements of steelmakers and is not exported due to better market conditions abroad). By assuming this value, the total secondary production is 25 Mt in 2050, which meets the demand for steel from all types of hot rolling mills except mills producing coils.[11]

An additional *Monte Carlo analysis* carried out 1000 different model runs with random combinations of random finished steel production volumes (randomised on the level of the seven finished steel products), random scrap availability and random interest rates, all of them combined with the same assumption about technology choice (electrification). The original base case parameter value was used as a mean and a standard deviation for the random deviation from the mean value (normally distributed). Therefore, the Monte Carlo analysis provides an additional set of 1000 sensitivity cases (see Table 3 and below).

## 3. Results

### 3.1. Scenario results

The following section focuses on the *electrification base scenario* with its implications for the general technology replacement, the geographical impacts and vertical integration. The analysis reveals that site types as well as countries are affected very differently by such a strategy. The results of the electrification scenario are contrasted in selected contexts with the *reference base scenario* and its underlying reinvestment in the blast furnace route.

Production stock turnover in the electrification base scenario for the region of Northwestern Europe is shown in Fig. 4. Existing overcapacities in the primary steel production route up to 2025 are mothballed; therefore no further relining of blast furnaces occurs. Reinvestment in the DRI route starts after 2025 and by 2040 the blast furnace route is completely phased out in accordance to regular reinvestment cycles. Secondary steel production capacities increase in

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[11] Scrap can – at least in part – be used for coils and some potential studies assume higher secondary steel potentials than assumed here in the base scenario (Material Economics, 2018).

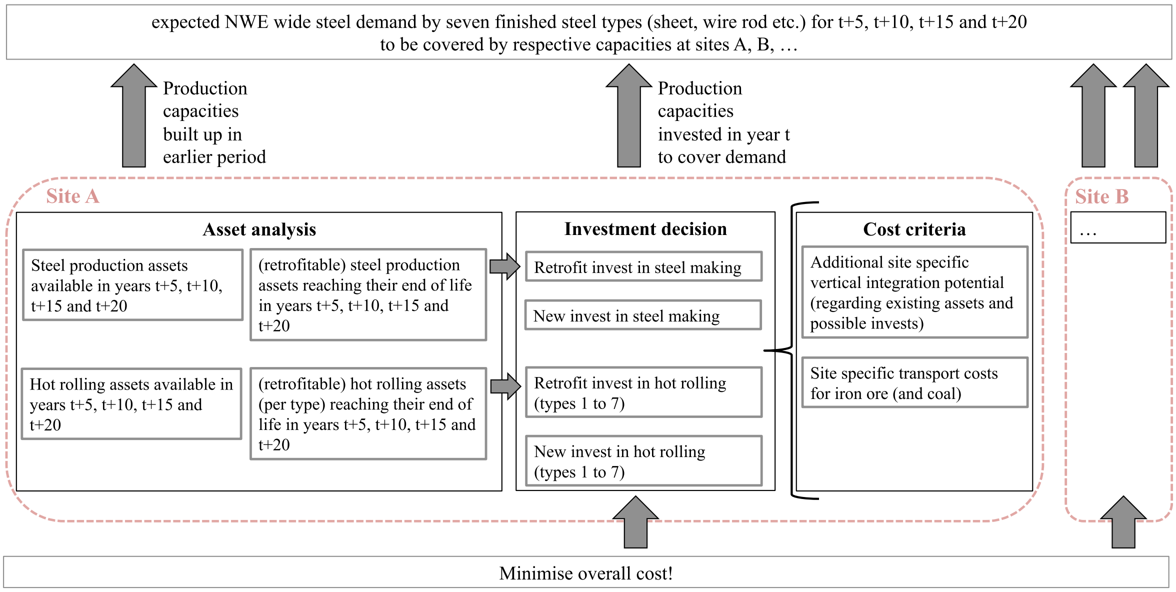

**Fig. 3.** Simulation of the investment decision in one period [source: own figure].

**Table 3**
Cases and scenarios.

| | Reference base scenario | Electrification (H-DR) base scenario | Monte Carlo analysis |
|---|---|---|---|
| **Projection of finished steel production** | default case (stable production) | | *stable production with standard deviation according to historical values for five-year periods* |
| **Technology pathway assumptions** | business-as-usual (primary crude steel making **via the blast furnace route)** | **electrification:** H-DR as standard technology from 2025 onwards | as per electrification base scenario |
| **Scrap availability** | increase by 1.6% p.a. | | *average growth rate of 1.6% p.a., standard deviation 0.04* |
| **Interest rate** | 8% | | *average interest rate of 8% ,standard deviation 0.1* |

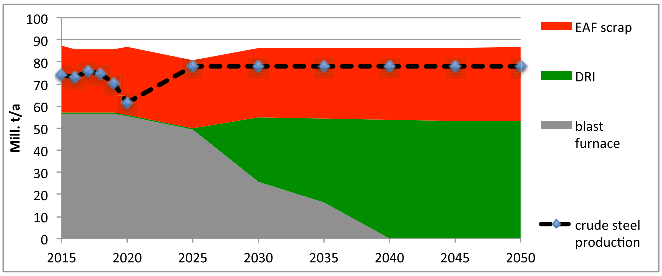

**Fig. 4.** Production stock turnover for crude steel making in the electrification base scenario [source: own calculations].

particular after 2030 as a consequence of more available scrap.

In contrast to other *deep decarbonisation scenarios* for the steel sector (see e.g., Morfeldt et al., 2015; van Ruijven et al., 2016), in this scenario the total decarbonisation of the sector is achieved by 2050. One reason for this is that the model (unlike others) does not assume blast furnaces to have a lifetime of 40 years; it assumes a more realistic lifetime of two times 20 years. Every blast furnace needs relining after continuous operation for 20–25 years.

The geographical category of analysis introduced above is the site type. Fig. 5 indicates capacity development according to this category. For hot rolling, differentiation is made between hot rolling sheet (typically connected to primary production) and other hot rolling mills. The figure shows that until 2030 only capacities at coastal and wet inland sites are converted to DRI because of lower transport costs for ore, whereas the rail inland sites lose primary steel and hot rolling capacity. After 2030, the inland sites catch up again: some inland non-integrated hot rolling sites are closed but others are strengthened by new investment in primary or secondary steel capacities and profit from increased vertical integration. After 2040, the rail inland sites benefit from the better availability of useful steel scrap and build up new capacities. The map in the supplementary material indicates that increased vertical integration at rail inland sites takes place in Belgium (Charleroi) and in the Rhine-Ruhr region (Bochum). These sites are re-integrated due to investment in primary crude steel production capacities. The most competitive sites at the coast, as well as the wet inland sites at the River Rhine, retain their status as “integrated sites”.

In terms of total capacity, the vertical integration of production capacities reaches 79% in the electrification case compared to 78% in the blast furnace route (BF) reference case by 2050. This represents an increase compared to 2030 (71% in the electrification case and 72% in the reference case) and 2015 (60%).

To identify how a restructuring of the electrification scenario will affect the national level, Table 4 shows the country-specific net investment/de-investment in primary and secondary crude steel making and hot rolling as simulated by the scenario modelling, which includes competition for investment between sites. Existing capacities in the base year are contrasted with the two periods 2015–2030 and 2030–2050, indicating net capacity changes.

Germany is the biggest producer in the region but also faces the biggest challenges: its annual capacity of crude steel is reduced by 5 million tonnes by 2030 (10%), whereas hot rolling capacities increase. Four non-integrated sites are closed (see Table 5). This development is significantly worse than in the reference scenario, where the steel capacity reduces by only one million tonnes. In the following 20 year period, the primary steel capacity reduces even more in the electrification scenario compared to the reference scenario, whereas secondary capacities grow in both scenarios (compensating in part for the

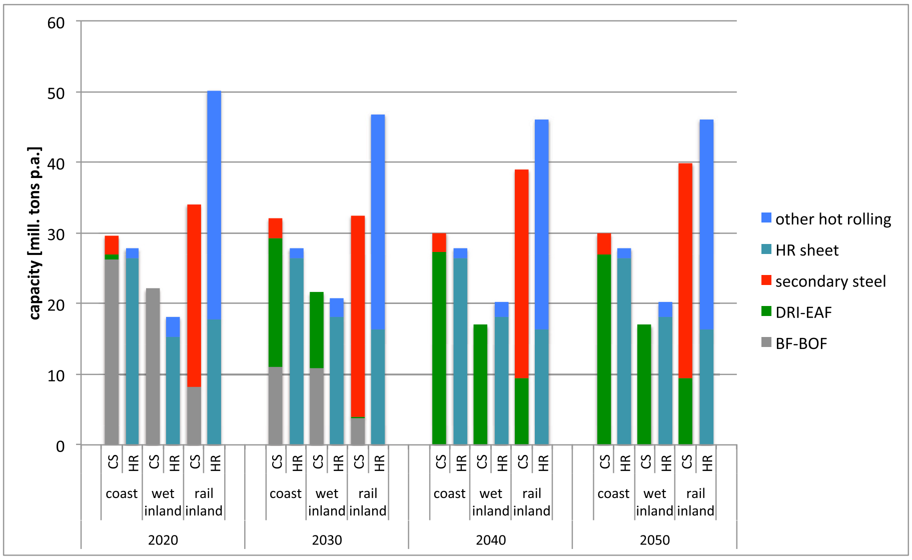

**Fig. 5.** Crude steel making capacities in the electrification base scenario by site type [source: own calculations].

reductions in the primary route).

In France, the development is quite flat in the electrification case up to 2030, with the closure of only two very small non-integrated hot rolling sites (see Table 5). After 2030, the electrification scenario indicates capacity increases in primary production; in contrast, the reference scenario shows a slight decline. For Belgium, the electrification scenario offers the potential to re-integrate a non-integrated hot rolling site (see map in the supplementary material), meaning that Belgium's steel industry (specifically in the Charleroi region) could profit from an electrification scenario compared to the reference scenario. In both periods (2015–2030 and 2030 to 2050), primary steel production grows in capacity. On the other hand, Belgium is the only region where losses (albeit small) in the secondary route occur. The Dutch steel industry is currently consolidated and concentrated at the very advantageous Ijmuiden site. The electrification scenario does not indicate much development before or after 2030. In the reference scenario, however, this site would loose one third of its capacity until 2030, due to the fact that the whole blast furnace route at the site would have to be reinvested, including the coking batteries. In light of shrinking primary steel production requiring some de-investment, the partial refurbishment of other sites is the preferred option in this particular case. Luxembourg's steel industry is comparatively small, but in relation to population and GDP it is a crucial industry sector for the country. In both the reference and electrification scenarios it loses some hot rolling capacity but gains in electric arc furnace capacity.

### 3.2. Sensitivities

The Monte Carlo analysis tests the robustness of the results under different economic conditions and developments and reveals that the strengthening of rail inland sites through electrification observed in the electrification base scenario (see above) is a robust development. Primary steel production generally returns inland after 2030, even in cases characterised by crisis or low steel demand.

The different steel market conditions analysed in the following are characterised by demand for steel products, scrap availability and interest rates. Typical developments in the steel market can be expressed as combinations of certain parameter values and, consequently, the concurrence of certain parameter value ranges can be subsumed in *classes of cases*. The results of the Monte Carlo analysis were clustered ex-post and the classes derived are shown in Table 6, together with their respective characteristics.

The first column in the table indicates three different characteristics in the development of the steel market. "Crude steel production growth" is not actually a parameter but results from steel demand, which is randomised. Consequently, there is a certain correlation between this characteristic and the second (deviation in production over time); it is nevertheless possible for crude steel production growth to be high, but deviation in demand over time to be low. The third characteristic (scrap availability for secondary steel production) is a randomised parameter and does not correlate with the other characteristics.[12]

The first class, labelled "middle of the road" (MOR), is similar to the base case scenario, indicating the most likely outcomes in a non-disruptive market development of the steel industry. The following class, "*steel crisis*", is characterised by three specifications that can be rated as unfavourable for steel industry stakeholders: a negative trend in steel production, high volatility of demand for different steel products (high uncertainty) and low availability of scrap (which is a logical concurrence). The second class of sensitivity cases is labelled "*de-materialisation*" representing cases with a decline in steel demand – but following a clear trend, which allows for predictability. Consequently, scrap availability is lower than average. Such a trend could be backed by new business models for re-selling used steel components (Ness et al., 2015). Despite strong overall steel production growth, the third class, "*chaotic growth*", is challenging as it represents high uncertainty for individual stakeholders. The high deviation represents structural changes in demand for different hot rolled steel products and/or strong business cycles. The "*business cycles*" class is characterised by a high deviation in product demand over time, resulting in cyclical development and/or structural changes in the production of the different steel products. Finally, the class labelled "*scrap crisis*" is a unique case characterised by low availability of scrap despite high growth in steel production. This class occurs in situations with high net export of steel (in products like cars) or high net export of scrap. Both these drivers have been recently observed in Europe.

Table 7 presents the aggregate results of 1000 model runs and compares these to the "electrification" base scenario. The focus is on the primary route as this route includes significantly more jobs – meaning

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[12] Scrap availability was an exogenous input to the model. Although growth in demand and scrap availability do correlate in reality over time (with a time lag representing the lifetime of the products containing steel), changes in steel export and import ratios may overstate the correlation. It is, therefore, reasonable to randomise the two parameters separately and classify the cases after running the model.

**Table 4**

Capacity changes (in million tonnes of annual production capacity) in the NWE countries during the 2015–2030 and 2030–2050 periods in the two base scenarios[a] [source: own calculations].

| | Base year capacity in stock | | | Capacity change 2030 vs. 2015 | | | | | | | | Capacity change 2050 vs. 2030 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | primary | secondary | hot rolling | total CS | | primary | | secondary | | hot rolling | | total CS | | primary | | secondary | | hot rolling | |
| | | | | BF | DRI | BF | DRI | BF | DRI | BF | DRI | BF | DRI | BF | DRI | BF | DRI | BF | DRI |
| GER | 34.4 | 15.1 | 53.6 | −1.0 | −4.9 | −1.1 | −4.9 | 0.0 | 0.0 | 1.6 | 1.6 | −0.7 | −1.5 | −2.1 | −3.0 | 1.4 | 1.4 | −0.5 | −0.5 |
| FR | 12.7 | 7.7 | 19.0 | 0.6 | 0.2 | 0.3 | −0.1 | 0.3 | 0.3 | −0.7 | −0.7 | −0.1 | 1.3 | −0.5 | 1.0 | 0.3 | 0.3 | 0.0 | 0.0 |
| BE | 4.3 | 5.1 | 12.7 | −0.4 | 1.3 | 0.2 | 1.9 | −0.6 | −0.6 | 0.0 | 0.0 | −0.2 | 0.6 | −0.1 | 0.6 | −0.1 | −0.1 | −0.8 | −0.8 |
| NL | 6.0 | 0.0 | 6.8 | −1.9 | 0.6 | −1.9 | 0.6 | 0.0 | 0.0 | 0.0 | 0.0 | 1.3 | −0.1 | 1.3 | −0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| LUX | 0.0 | 3.7 | 3.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | −0.6 | −0.6 | 0.3 | 0.3 | 0.0 | 0.0 | 0.3 | 0.3 | 0.0 | 0.0 |

[a] “BF” denotes the reference scenario with reinvestment in the blast furnace route; “DRI” denotes the electrification base scenario with reinvestment in the DRI route.

**Table 5**

Overview of site status change within the time periods 2015–2030 and 2030–2050 in the NWE countries (number of sites in the electrification scenario) [source: own calculations].

| | | Belgium | | Germany | | France | | Luxembourg | | Netherlands | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2015–2030 | 2030–2050 | 2015–2030 | 2030–2050 | 2015–2030 | 2030–2050 | 2015–2030 | 2030–2050 | 2015–2030 | 2030–2050 |
| Site up-grade | from non-integrated to integrated | 0 | 1 | 4 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| Status quo | remain integrated | 4 | 4 | 15 | 18 | 12 | 12 | 2 | 1 | 1 | 1 |
| | remain non-integrated | 3 | 1 | 19 | 18 | 7 | 7 | 2 | 2 | 1 | 1 |
| Site downgrade | from integrated to non-integrated | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 |
| | from non-integrated to closed | 0 | 1 | 4 | 0 | 2 | 0 | 0 | 0 | 0 | 0 |
| | from integrated to closed | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | total | 7 | 7 | 43 | 43 | 21 | 21 | 4 | 4 | 2 | 2 |

**Table 6**
Classification of Monte Carlo model runs.

| Characteristics | Classes of sensitivity cases[a] | | | | | |
|---|---|---|---|---|---|---|
| | Middle of the road | Steel crisis | De-material-isation | Chaotic growth | Business cycles | Scrap crisis |
| Crude steel production | mid | low | low | high | – | high |
| Deviation in production of single HR products (over time) | mid | high | low | high | high | – |
| Scrap availability growth rate | mid | low | low | high | – | low |

[a] Cases in the upper 25% of the values of the sensitivity cases are labelled as "high", the lowest 25% are "low" and the 50% in the middle of the set are "mid". The classes include all the sensitivity cases with the relevant combination of characteristic values.

**Table 7**
Degree of vertical integration and mean share of primary steel making capacities according to site type of different classes (Monte Carlo analysis of electrification scenario).

| | Share of capacity at integrated sites | | | Capacity share of site types | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2015 | 2030 | 2050 | 2015 | | | 2030 | | | 2050 | | |
| | | | | Coast | Wet inland | Rail inland | Coast | Wet inland | Rail inland | Coast | Wet inland | Rail inland |
| today | 60% | | | 45% | 41% | 14% | | | | | | |
| base case | | 71% | 78% | | | | 53% | 39% | 7% | 51% | 32% | 18% |
| mean all sensitivities (n = 1000) | | 73% | 76% | | | | 53% | 37% | 11% | 52% | 31% | 17% |
| cluster middle of the road (n = 135) | | 73% | 78% | | | | 53% | 37% | 10% | 50% | 31% | 20% |
| cluster steel crisis (n = 58) | | 71% | 72% | | | | 53% | 36% | 12% | 54% | 31% | 15% |
| cluster dematerialisation (n = 17) | | 69% | 72% | | | | 55% | 36% | 10% | 54% | 32% | 14% |
| cluster chaotic growth (n = 38) | | 74% | 73% | | | | 53% | 37% | 10% | 52% | 31% | 17% |
| business cycles (n = 249) | | 74% | 76% | | | | 51% | 37% | 12% | 50% | 30% | 19% |
| cluster scrap crisis (n = 72) | | 77% | 77% | | | | 48% | 36% | 16% | 46% | 29% | 24% |

that industry and politics are highly sensitive to changes in this route.

The table shows that the randomisation of the three parameters (demand for steel products, interest rates and scrap availability) does not result in systematic deviations in the allocation of primary steel capacities to the three site types – the mean of all sensitivities is almost equal to the base case in this respect. On the level of the clusters of cases, the mean shares of the 1000 runs are also similar to the base scenario values. Nevertheless, the strengthening of rail inland sites through electrification observed in the electrification base scenario (see above) is a robust development. Even in cases characterised by crisis or low steel demand, primary steel production generally returns inland. The table also shows that the greatest deviations from the base scenario in terms of primary steel capacity allocation are in the "*scrap crisis*" class, where significant new capacity in primary steel making has to be developed. These cases also achieve the highest rates of vertical integrated production.

The graph in the supplementary material shows some extreme cases; for example, where the coast reaches 70% of capacity share in primary steel production and rail inland sites stay below 10%. These represent however rather counterintuitive cases with a decreasing steel production in the region and rather high scrap availability. Such a combination could turn out in reality if scrap could be used much more efficiently or if additional scrap could be imported to the region.

## 4. Discussion

The approach taken has its limitations but offers several starting points for further research. Ignoring the possible future price ranges of hydrogen between different regions is an important simplification. Differences within the region of Northwestern Europe can be expected to be small if a hydrogen pipeline infrastructure is established, but the range in cost could be high compared to non-EU countries with cheap renewable sources for electricity if these countries actively pursue electrification and try to increase their market shares. Such competition could result in increased slab or DRI/HBI import to Northwestern Europe; an analysis of this development was beyond the scope of this paper. Another simplification in the modelling is the setting of the geographical boundaries: the focus on the NWE countries may be justified by current major trade flows but should be critically reviewed as future electricity or hydrogen price differences between different regions within the EU will probably be higher than within Northwestern Europe. Crucially, $CO_2$ mitigation regulation in the steel industry is likely to be at the European level and as intra-EU tariffs to protect industries are not feasible in the EU single market, stronger shifts within Europe as a whole could occur. A general limitation of most scenarios on the steel industry is the lack of feedback between technology change in primary steel making and the shares of secondary steel making in total steel production. While studies in the field of industrial ecology (Pauliuk et al., 2013; Daehn et al., 2017) have elaborated on the technical potential of using secondary steel, the current projections about future primary steel demand in the EU remain simplistic, and secondary production is still generally considered as a separate market and simply as a form of downcycling.

This study could be a starting point for additional future analysis, deepening the understanding of possible industrial relocation. The model could be geographically enlarged to encompass the whole of the EU and could also be enriched by an additional dimension: the quality of steel and scrap. Taking this dimension into account would help to better understand the techno-economic inter-relationship between primary steel decarbonisation and the circular economy. This would allow for analysis of the potential for a region to adopt one or other option, or a mixture of both. The existing model could also be used to conduct further studies explicitly addressing possible large-scale slab or DRI/HBI import to Northwestern Europe. A study by Gielen et al. (2020) stressed the potential opportunities for countries with iron ore resources and cheap renewable energy, like Australia, to pursue a high-value export strategy instead of only exporting raw materials (i.e., iron ore). Finally, on the global level, developments in the Chinese and Indian steel industries are much more significant in terms of global GHG mitigation than those in the small "frontrunner" region of focus here. Suitable fields of study for a model such as the one described in this paper could be the transformation of similar large inland markets with established spatially differentiated structures, such as in the eastern countries of the EU or in the USA, Russia, Ukraine and China.

## 5. Conclusions

The model developed provides a tool to simulate investment in steel making and hot rolling capacities at 84 sites within the region of Northwestern Europe. With its ability to simulate spatial reorganisation of the production chain it represents a new model kind in this research field that can feed into discussions about regional affectedness of the transformation towards a climate neutral steel industry in Europe.

The modelling results show that a development to further integration of steel making and hot rolling at sites is likely if existing assets of the blast furnace route are devaluated. The development of the model and the discussion of the results with stakeholders revealed that companies considering an investment in green steel making technologies have to engage in complex decision-making processes about when and where to invest. It is understandable that the general lack of national and EU technology and infrastructure roadmaps targeting GHG neutrality in industry adds further to the insecurities and concerns of companies, industry associations and trade unions in terms of adopting or backing these technologies.

The analysis in this paper makes this complexity explicit and reveals that it is over-simplistic to assume that hydrogen-based steel making will be the preferred option for a specific site type (e.g., coastal sites) if energy (i.e., hydrogen) is available at a similar price throughout the region. Therefore, the specific strategies implemented by individual companies and sites can really make a difference, as good management or a superior regional infrastructure strategy may compensate for small cost differentials.

Consequently, in terms of regional policy, stakeholders such as steel producing companies, trade unions and regional development agencies – as well as energy infrastructure operators – should be encouraged to promote technological change in inland steel making clusters (such as those in western Germany or southern Belgium) to achieve GHG neutrality, which also includes transformation strategies to adopt secondary production. Such encouragement can accelerate vertical integrated production at sites and thus save jobs in certain regions and increase overall energy efficiency of production. A process involving the steel companies has already started: European-based steel companies and the European steel association, Eurofer, are developing their visions for GHG neutral steel production and some companies have even published their initial indicative roadmaps or announced that they are planning to invest in certain technologies at specific sites. Political stakeholders can play an important role in reducing uncertainties about future boundary conditions by setting roadmaps at different geographical levels and encouraging stakeholder engagement. Planning hydrogen pipeline grids is still at a conceptual stage in Germany and it is logical for companies and political entities to hedge the risk of uneven hydrogen prices throughout the region of Northwestern Europe. The Monte Carlo analysis in this study revealed that strong business cycles are an additional threat to potentially less favourable inland sites. Although this risk might be clearly perceived by stakeholders and experts involved in the planning processes, it is typically not explicitly addressed in regional roadmapping exercises. The results of the model described could be used as additional input to inform political and societal stakeholders in their discussions with companies and trade unions.

## CRediT authorship contribution statement

**Clemens Schneider:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review editing, Visualization.

## 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. Supplementary data

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