Industrial site energy integration – the sleeping giant of energy efficiency? Identifying site specific potentials for vertical integrated production at the example of German steel production

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Abstract
Heat integration and industrial symbiosis have been identified as key strategies to foster energy efficient and low carbon manufacturing industries (see e.g. contribution of Working Group III in IPCC's 5th assessment report). As energy efficiency potentials through horizontal and vertical integration are highly specific by site and technology they are often not explicitly reflected in national energy strategies and GHG emission scenarios. One of the reasons is that the energy models used to formulate such macro-level scenarios lack either the necessary high technical or the spatial micro-level resolution or both. Due to this lack of adequate tools the assumed huge existing potentials for energy efficiency in the energy intensive industry cannot be appropriately appreciated by national or EU level policies.

Due to this background our paper describes a recent approach for a combined micro-macro energy model for selected manufacturing industries. It combines national level technical scenario modelling with a micro-modelling approach analogous to total site analysis (TSA), a methodology used by companies to analyse energy integration potentials on the level of production sites. Current spatial structures are reproduced with capacity, technical and energy efficiency data on the level of single facilities (e.g. blast furnaces) using ETS data and other sources. Based on this, both, the investments in specific technologies and in production sites are modelled and the evolvement of future structures of (interconnected) industry sites are explored in scenarios under different conditions and with different objectives (microeconomic vs. energy efficiency optimization). We further present a preliminary scenario that explores the relevance of these potentials and developments for the German steel industry.

Introduction
German steel industry as a system and also past investments in energy efficiency in crude steelmaking as well as remaining efficiency potentials have been well investigated (e.g. Arens et al. 2014). The efficiency potential of vertically and energy integrated steel production is theoretically significant. In the concept of energy integrated hot rolled steel production (see Figure 1) the hot steel is directly fed into a rolling process either by charging hot material into the reheating furnace or by direct rolling of the hot steel instead of casting slabs, let them cool down and reheat them later to enable rolling. Both concepts save most of the energy typically used for reheating of cold steel slabs in the rolling mill. In spite of its potential savings the concept does not play a prominent role in the literature. One source (EPA 2012) that is often cited estimates the specific energy efficiency potential of integrated production with hot charging of the metal in a hot rolling mill to be 0.06 GJ per ton of hot rolled (HR) steel. The estimate given in EPA's paper is not explicated, in particular the assumed rate of hot charging is not documented. Taking into account the overall energy consumption of hot rolling – 1.5 GJ/t HR steel for an average EU conventional hot strip mill (De Lamberterie 2014) – or of the overall process of steelmaking in the primary blast furnace/basic oxygen furnace (BF/BOF) route (>15 GJ/t) it seems to be reasonable to neglect the savings potential of hot charging.

On the other hand steel manufacturers have taken efforts during the oil crisis in the 1970s to develop hot charging concepts working continuously to adapt hot rolling to continuous casting. The latter technology was introduced in Germany in 1964 and has diffused in the German steel industry within 30 years (Arens et al. 2014). Besides the concepts of direct rolling there are concepts to thermo-insulate the casted slabs when storing them and transporting them to the HR mill.

Actual energy saving in the hot rolling mill depends on the temperature of the slabs when arriving at the HR mill and the share of hot slabs used. De Lamberterie (2014) gives a value of 0.05 GJ/per % of hot charging (550 °C) as a general estimation which equals to a saving of 0.25 GJ/t HR steel considering a hot charging rate of 50 %. Direct hot charging (i.e. direct rolling) allows for even higher savings: in bringing continuous casting and hot rolling together and synchronizing the schedules slab temperature of 1,100 °C and hot charging rates of 85 % can be achieved (Zhao et al. 2015). Reheating in the HR mill can then be almost omitted which can save 90 % of energy in the hot rolling step. Direct rolling concepts however require greater investments and are only realisable if there is enough space at the casting site.

Besides the energy saving benefits of hot rolling site integration can imply transport energy savings. Transport energy savings potentials depend on the distance of the crude steelmaking site to the HR mill site and on the distance of the HR mill to the consumer. As we did not account for todays and future spatial distribution of finished steel consumption, this aspect is not covered in the model.

If the above mentioned energy efficiency potential of integrated HR steel production can be realized depends not only on technology but also on the spatial distribution of future investments in crude steel and hot rolling capacities. Today in Europe many hot rolling sites are isolated without any on-site crude steel production. In Germany there are 18 isolated HR sites (with a minimum capacity of 50,000 t/y each). Many of these sites have been isolated by structural changes, e.g. with the shift from primary to secondary steelmaking, the closing down of iron and coal mines and the concentration of BFs at "wet" sites which can be supplied by vessels. In the future further structural changes could occur in the steel industry: If steel industry is to be decarbonized until 2050, today's prevailing BF/BOF primary steel route has to be complemented or even replaced by new technologies (see e.g. Lechtenböhmer et al. 2015, Quader et al. 2015, Fischedick et al. 2014). Some of these like e.g. hydrogen based direct reduction of iron could need new greenfield investments, which may result in a new spatial distribution of capacities in the future. Such changes might be triggered by new influencing factors such as the availability of abundant electricity from fluctuating sources of hydrogen or gases produced from these energy sources.

In this paper we investigate how different futures of steel making would influence the options to stronger integrate steel making and to exploit its efficiency potentials. For this we use a microeconomic optimization model, showing how investments could evolve if individual actors optimize their investments under uncertainty about the future. We consider different crude steelmaking pathways and several demand projections for six different hot rolled products (sheet, plates, bars, structures, seamless tubes and wire rod). First the model and the underlying methodology are described, then we provide an overview of the technological as well as spatial structure of German steel industry and present the results of two spatially explicit scenarios and a number of sensitivities on possible future pathways of German steel production. Based on this we discuss the influence of different pathways on the options to better integrate steel production and hot rolling.

Methodology

SYSTEM ANALYSIS

As today three routes of producing crude steel can be observed in Germany, two primary steel and one secondary (scrap) steel route:

1. the traditional route of making pig iron form iron ore (via pelletization or sintering) in a blast furnace (BF) and further processing in a blast oxygen furnace (BOF),
2. the so called direct reduction of iron ore (DRI) with natural gas as a reducing agent – as a more innovative route with lower GHG emissions – with further smelting of the sponge iron in an EAF and
3. the traditional route of recycling steel scrap (secondary steel) in an electric arc furnace (EAF).

From today's point of view there are different technologies to achieve a deep decarbonisation of primary steel production[1], e.g.:

1. direct reduction of iron ore to sponge iron and the usage of CO_2 free hydrogen as reducing agent (instead of coal)
2. the capture of CO_2 in the off-gas of blast furnaces and storage (CCS) or bonding it in a carbon containing product (CCU)
3. the electro-chemical way of electrolysis which does without any reducing agent.

Subsequently to crude steel making the hot metal has to be casted. Most of crude steel is rolled afterwards and the standard feed of a hot rolling mill is casted slabs. Continuous casting (CC) has been introduced in Germany in the 1960s and is today's standard casting technology to produce slabs. The advantage of CC is that the casting process has not to be stopped when one charge of hot metal has been processed. So slabs in the desired form can always be casted without losses.

If steelmaking and hot rolling capacities fit well at a site hot charging or direct hot rolling is a further option to reduce energy of reheating slabs in the hot rolling mill.

As so far direct rolling is not a standard technology in Germany. Whereas in Japan and China there are several hot strip mills fed directly with hot metal, in Germany only Thyssen-Krupp's Duisburg site is partly equipped with such kind of energy efficient technology.

One reason is that hot rolling mills have very long technical lifetimes of 50 years. Another reason is that especially BF/BOF sites provide very cheap fuel: BF and BOF gas are produced as

1. A comprehensive overview on alternative steel making technologies is given by Quader et al. (2015).

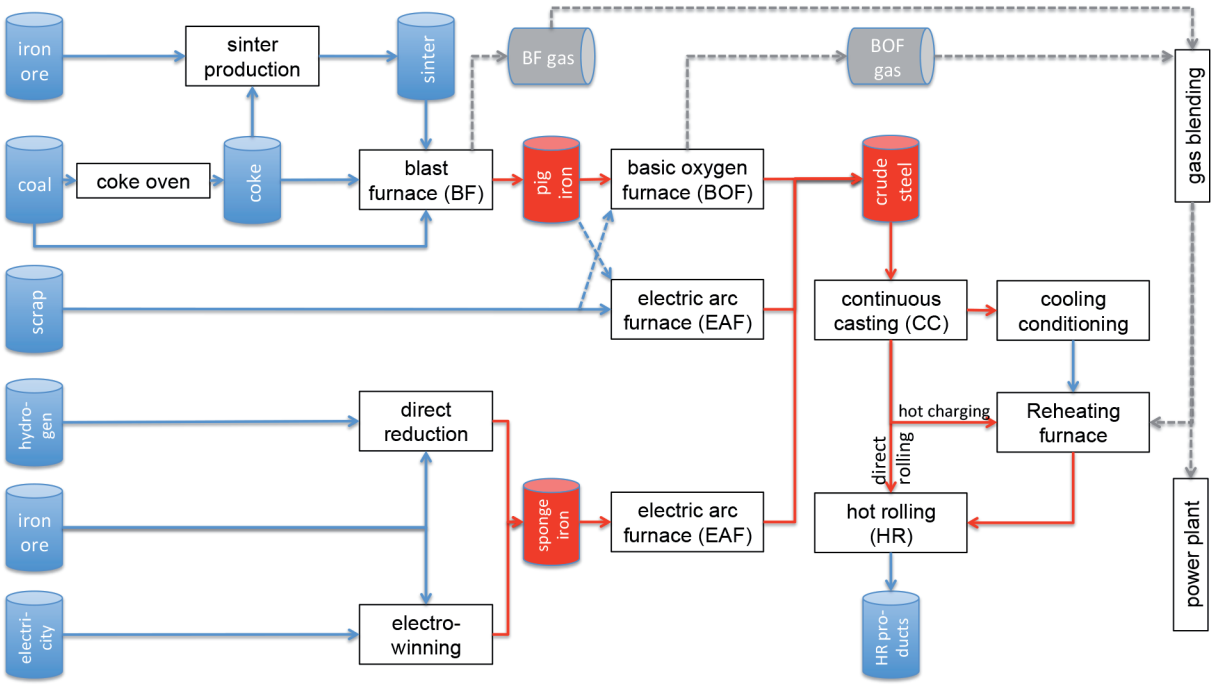


Figure 1. Flows of various routes of crude steel production and hot rolling [source: Quader et al. 2015, Zhao et al. 2015, adapted and amended].

a by-product in the process. These gases have very low energy content in relation to their volume and thus can be stored only for short periods of time. Hot rolling on the other hand represents a quite continuous "sink" for this gas. When firing reheating furnaces with BF and/or BOF gas almost all energy content is converted to useful energy. The alternative way of using BF/BOF gas is firing a gas power plant, implying higher energy losses. BF/BOF gas power plants cannot be operated according to electricity demand in the market. In the long term – with high shares of renewable energies in the electricity market – inflexible BF gas fired power plants may even crowd out renewable electricity generation with a respective GHG burden.

Besides capacity site integration, "gas integration" is therefore a second energy efficiency criterion in the model.

It has to be stressed that these by-product gases do not occur in alternative routes of steel making like DRI (with hydrogen), iron electrolysis, or the routes with carbon capture. So the second criterion of "gas integration" is generally irrelevant in the respective paths.

Carbon capture is not regarded in our model. The specific costs for this technology are also site specific. They depend on the distance to geological storage capacities or to possible carbon sinks (in the chemical industry). Particular research is required on the potentials of horizontal integration of steel and chemical industry.

INVESTMENT MODEL

The developed model simulates the investment in iron reduction technology and electric arc furnaces as the key technologies in crude steel making. After the determination of investment in crude steel making the investment in the six different hot rolling mill types is determined.

The model considers different factors influencing investment decision:

- The amount of "free" capacities which can be retrofitted (capacities can be retrofitted within a five-year period after the expiration of technical lifetime).
- The amount of "free" capacities which are disposable for an integrated production (hot rolling mill or blast furnace/blast oxygen furnace respectively).

There are two additional criteria:

- The amount of "free" capacities which can deliver blast furnace gas or basic oxygen furnace gas which is cheaper than natural gas (criterion for investment in hot rolling mills).
- The amount of "free" periphery stock disposable (i.e. coke ovens, sinter plants and BOF), as a criterion for investment in blast furnaces.

Retrofit potentials occur at a site if technical lifetime of a plant exceeds. It is assumed that five years after expiry of lifetime the retrofit potential is extinguished. After then investments at the site in the same kind of stock will be rated as greenfield investments.

A further criterion is transport costs, which are influenced by geography and infrastructure. Seaports have the lowest transport costs; sites served by truck have the highest costs in regard to bulk materials like coal and iron ore (s. above).

Expected future income flows like savings from BF gas use or costs (like transport costs) are rated with their net present value by the time of investing.

The model does not consider actors or agents. It assumes perfect (economic) rationality of investments, but with restricted knowledge (of all parties) about the future. A linear programming (LP) optimization procedure in R is used to solve both optimization problems, i.e. discrete variables have to be used.

Microeconomic optimization procedure

The following formula (1) represents the target function of the microeconomic optimization procedure:

$$IC_{CS} = \sum_{i=1}^{50}((CI_{EAF\,i} \times SI_{EAF} - RPU_{EAF\,i} \times SSR_{EAF}) + (CI_{BF_i} \times (SI_{BF} + STC_{coal\&\,iron_i}) - RPU_{BF_i} \times SSR_{BF} - PPU_{BF_i} \times SSP_{BF_i}) + (CI_{DRI_i} \times (SI_{DRI} + STC_{iron_i}) - RPU_{DRI_i} \times SSR_{DRI}) + (CI_{EL_i} \times (SI_{EL} + STC_{iron_i})) - HCPU_i \times SSHC) \quad (1)$$

With:

IC_{CS}	Investment costs for crude steel capacities
CI	capacity investment (in capacity of metric tons/a=yt)
SI	specific investment costs (in EUR/(yt))
RPU	retrofit potential used (yt)
SSR	specific saving if retrofit is used (in EUR/(yt)
PPU	existing periphery of the BF/BOF route which is integrated by BF investment (yt)
SSP	specific saving by integrating existing BF periphery (in EUR/yt)
HCPU	Hot rolling capacities which are integrated by additional CS capacity investment (yt)
SSHC	specific saving by hot charging (in EUR/yt; net present value (time horizon: 10 years) and savings by transport reduction between crude steel site and hot rolliung site
STC	Specific transport costs (per tonne of iron and coal or per tonne of iron)

The CI and RPU/PPU and HCPU terms in the formula represent the variables of the target function, i.e. the target function consists of 450 variables (9 variables for each of the 50 sites). The product PPU_{BF} x SSP_{BF} consists of two weighted terms according to the existing capacities of coke ovens, sinter plants and blast oxygen furnaces at a site and their specific investment costs respectively.

The following constraints ensure that only savings are accounted in the target function if saving potential exists and is equal to the amount of other capacity which is actually integrated by the new investment.

$$CI_{ij} \geq RPU_{ij} \quad (2)$$

$$CI_{BF,i} \geq PPU_i \quad (3)$$

$$\sum_{j=1}^{4} CI_{ij} \geq HCPU_i \quad (4)$$

$$RPU_i \leq RP_i; PPU_i \leq PP_i; HCPU_i \leq HCP_i \quad (5)$$

With:

RP	retrofit potential (capacity of metric tons/a=yt)
PP	periphery integration potential, i.e. "free" coke oven, sinter and BOF capacities (in yt)
HCP	hot charging integration potential, i.e. "free" hot rolling capacities (in yt)

Hot rolling investment is determined analogously in an integrated optimization for the six different types. For every single type capacity need is calculated respectively and retrofit options are regarded separately. So a hot strip mill may not be converted into a bar mill via retrofit.

Limitations of the model

The model does not simulate the kind of technology, which is built. Especially the change of routes from BF/BOF to alternative steelmaking is not simulated, but given by a technology matrix. As technology routes, however, are crucial for the spatial dimension of investment decisions the analysis of different technology pathways is part of the sensitivity analysis.

Simultaneous decisions on investment in steelmaking and hot rolling technologies have not been regarded to simplify the optimization problem.

Company groups in reality do use periphery stock at one site to feed another. This can be observed especially regarding coke ovens. The model however does not regard an investment benefit for such assets. So if at the Bremen site of ArcelorMittal the BF has to be retrofitted, the model will calculate a supplementary investment in a coke oven, whereas today AM transports coke from its Bottrop site to Bremen to run the BF there.

Data

The German steel industry was investigated in depth to detect the relevant stocks, i.e. primary and secondary steel making capacities as well as hot rolling mills. Table 1 gives an overview of existing stock in Germany and its overall capacity utilization in 2014.

50 individual sites were accounted in the database; they are shown in Figure 2, indicating also the owning company groups. An additional map indicating today's spatial distribution of steel making and hot rolling capacities is presented in the results section below.

Many of today's EAF (e.g. Georgsmarienhütte, Hennigsdorf and Peine) or "isolated" hot rolling sites (e.g. Dortmund and Sulzbach-Rosenberg) are former sites of integrated steel mills (with primary steel making and hot rolling). Eastern German sites Hennigsdorf and Brandenburg have been converted from out-dated small BF/Siemens-Martin sites to modern EAF sites after the German reunification in the 1990s, whereas the Eisenhüttenstadt site, which had been equipped with Western BOF technology (from Austria) in the 1980s, remained the only primary steel site in Eastern Germany after 1990.

Other EAF sites have been greenfield investments especially during the late 1960s and 1970s in Western Germany (Hamburg, Kehl, Lingen, Lech-Stahlwerke).

Table 2 gives an overview on selected sites with their respective infrastructures and cost structures. Most of the steel making sites are "wet", i.e. they can be supplied by vessels. However, rail transport has replaced vessels in many cases because shipping on canals is more expensive than on the big rivers Rhine and Elbe. Today former "wet" sites like Dillingen or Eisenhüttenstadt are supplied by the heaviest freight trains on the German railway network. Block trains run directly from seaports like Rotterdam or Hamburg to the sites. The Duisburg sites are unrivalled inland sites in regard to transport costs (Table 2).

Table 1. Overview on iron & steel capacities in Germany [source: authors' enquiries, production volumes according to World Steel (2016) and AGEB (2015)].

		number of sites	number of plants	capacity (million tons/y)	capacity utilization (2014)	age (mean)*
primary steel making	Coke oven	5	9	8	91 %	20
	Sinter plant	7	10	31	n.a.	41
	Blast furnace (BF)	8	18	34	81 %	36
	Basic oxygen furnace	9	18	35	86 %	28
	DRI	1	1	1	94 %	45
secondary (scrap) steel making	Electric arc furnace (EAF)**	18	23	17	78 %	32
hot rolling (HR)	Sheet	87	8	27	76 %	44
	Heavy plate	5	5	6	52 %	28
	Structure	4	4	3	87 %	57
	Bar	10	10	8	57 %	39
	Wire rod	9	10	8	70 %	35
	Railway track***	–	–	–	–	–
	Seamless tube	5	5	1	95 %	63

** Retrofit not regarded here, but in the model when considering lifetime. The age of a little number of plants had to be estimated.*

*** Including EAF at the Hamburg DRI site.*

**** Mill closed in 2013.*

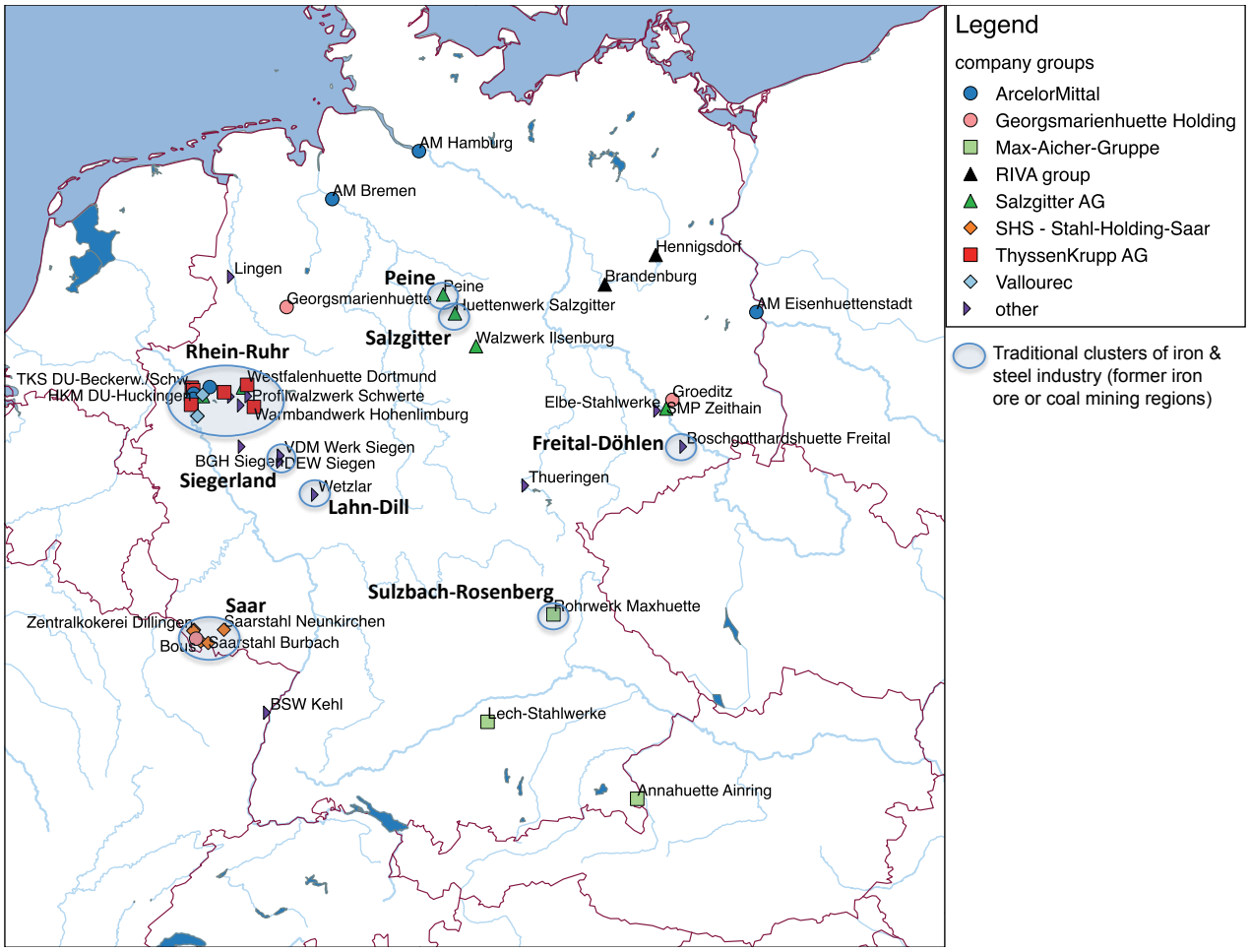


Figure 2. Steelmaking sites and clusters in Germany.

Table 2. Selected primary steelmaking sites with transport relations and their specific transport costs [source: authors' enquiries, PLANCO Consulting/ Bundesamt für Gewässerkunde (2007), StatBA (2015)].

	iron & steel cluster	Infrastructure					seaport	carrier	specific transport costs (EUR_{2012}/t)
		coke oven	BF/ BOF	EAF	HR strip mill	other HR mill			
Bremen	–		X		X		Bremen	–	–
Hamburg	–		*DRI*	X		X	Hamburg	–	–
Duisburg	Rhein-Ruhr	X	X		X		Rotterdam	vessel (push tow, 6 units)	3.75
Salzgitter	Salz-gitter	X	X		X		Hamburg	vessel (motor vessel+lighter)	4.83
Eisenhüttenstadt	–		X		X		Hamburg	railway (max. 6600 t train)*	8.00**
Dillingen	Saar	X	X				Rotterdam	railway (5400 t train)*	9.57

**) Gross weight (including weight of wagons).*

***) Own assumption.*

Table 3. Cases and scenarios.

Demand case	Base demand case (frozen)		demand sensitivities (30 cases)	
Supply case	"alternative crude steel making"	"BF/BOF"	"alternative crude steel making"	"BF/BOF"
assumptions	DRI/iron electrolysis as standard technologies from 2030 on (no more investments in BF plants from 2030 on)	No phase-in of alternative primary steel making technologies	Unlike electrification case aside	Unlike BF/BOF case aside
	increase in scrap availability by 1 % p.a.			

Scenario definition

The base demand case freezes 2012 demand of each hot rolled steel product until 2050. This is a rather conservative assumption. From 1998 to 2014 the so-called apparent use of hot rolled steel products in Germany (i.e. ASU = production + imports – exports) increased by 0.3 % p.a. (on base of an average value for a 4-year period). Whereas ASU of flat products (sheet, plates) increased by 0.7 % p.a. ASU of long products (bars, wire rod, structures) dropped by 0.3 % p.a. within the same period. However, the freezing of demand is only a general assumption to show model results in such a "simplified" world.

The frozen demand case was combined with two technology paths: One assuming the persistence of the existing BF/BOF path and one with a rapid adoption of new primary steel production technologies (i.e. DRI with hydrogen and iron electrolysis). So a very conservative case is contrasted with a very innovative one where DRI is the standard technology from 2030 on with no further investment in the BF/BOF technology. The choice of technology is made qua assumption in the scenario building and can be justified by price development (via the ETS) or policies (e.g. by the definition of best available technology). The model does not determine the choice of technology but only the spatial allocation of investment.

In all scenarios an increase of scrap availability by 1 % p.a. is assumed. Although scrap could also return from overseas to Germany this is a rather optimistic assumption. In fact Herbst et al. (2014) identify a huge additional potential for scrap use in Germany until 2035 but they assume a strong increase in demand of steel products in Germany as well.

The set of base scenarios consists of two different scenarios with common assumptions about demand and scrap steel availability and a differentiation between technologies. The sensitivity analysis combines 30 different cases of steel demand with the two technology paths providing an additional set of 60 scenarios (see Table 3 and below). Further parameters used in the target function of the optimization can be seen in Table 4[2]. Some are discussed below in the sensitivity section.

Results

Figure 3 and 4 show the allocation of steel capacities within Germany in the base year 2015 as well as for the two base scenarios "alternative CS" and "BF/BOF CS" for the scenario years 2030 and 2050 respectively. In the scenario year 2030 there are no differences between the two base scenarios as demand is the same and the technology path differs from 2030 on.

The base demand scenario freezes steel demand, which means that today's existing overcapacities have to be melted down over time. Micro-economic optimization provides no energetic optimum as the *oldest* capacities and not the *non-*

2. Specific energy use in BF/BOF plants and other steelmaking technologies is no relevant parameter in the optimization model. Respective values are cited in Lechtenböhmer et al. (2015).

Table 4. Parameters used in the optimization model.

	unit	*base year*	Scenario (2050)	source
interest rate	%	8	8	own assumption
amortization time of invest	y	20	20	stakeholders information
natural gas price	EUR-Ct_{2015}/kWh	3.2	5.8	Prognos/EWI/GWS 2014
share of hot charging	%	50%	50%	own assumption
specific invest BF	EUR/(t cap*a)	442	442	Wörtler et al. (2011)
specific invest coke oven	EUR/(t cap*a)	114	114	Wörtler et al. (2011)
specific invest sintering	EUR/(t cap*a)	51	51	Wörtler et al. (2011)
specific invest BOF	EUR/(t cap*a)	128	128	Wörtler et al. (2011)
specific invest EAF	EUR/(t cap*a)	184	184	Wörtler et al. (2011)
specific invest DRI (&EAF)		–	874	Weigel et al. (2014)
specific invest iron electrolysis		–	639	Weigel et al. (2014)
specific invest HR	EUR/(t cap*a)	180	180	Own assumption
saving retrofit BF	%	50	50	Wörtler et al. (2011)
saving retrofit coke oven	%	15	15	Wörtler et al. (2011)
saving retrofit sintering	%	30	30	Wörtler et al. (2011)
saving retrofit BOF	%	50	50	Wörtler et al. (2011)
saving retrofit EAF	%	50	50	Wörtler et al. (2011)
saving retrofit HR	%	50	50	own assumption
specific coal use	t/t pig iron	0.68	0.68	aggregated EU values for BF, sinter plants and coke ovens (JRC 2012)
specific iron ore use	t/t pig iron	1.695	1.695	weighted EU average based on JRC (2012)
specific energy saving by hot charging	GJ/t HR steel	0.5	0.5	de Lamberterie (2014)
specific revenue of electricity from steelworks' power plants	EUR/MWh	26	26	own assumption
full load hours of steelworks' power plants	h/a	5000	5000	own assumption
capex steelworks' power plants	EUR/kW	740	740	IEA (2010)*
opex steelworks' power plants	EUR/(kW*a)	29	29	IEA (2010)*

** 2010 US-dollar exchange rate of 1.35 assumed ($/EUR).*

integrated capacities are closed down first (and are not rebuilt again). This can be illustrated by the wire rod capacities in the "alternative CS" path. Instead of keeping up capacities in the Saar region (near Luxemburg) keeping of capacities at the Kehl site (EAF site in the southwest of Germany) would have been favourable in the long run.

The very strong concentration of capacities at Hamburg in the "alternative CS" path reflects that – without any retrofit benefits – transport costs outweigh other factors like benefits from integrated production. The location specific result has to be relativized. Capacity extension at one site during such a short time period is not reasonable because of companies' risk aversion and public acceptance. Steel industry could however spread to Bremerhaven and Wilhelmshaven or to other "north range" seaports in the Benelux (e.g. Rotterdam, Antwerp) with more competitive transport cost structures and build up greenfield sites – instead of a total revamp at the traditional sites.

Traditional primary steel sites in the former coal regions Rhein-Ruhr and Saar as well as in the former iron-mining region of Salzgitter would not survive as integrated sites in such a case. Turnover of primary crude steel capacities is quite fast, because blast furnaces need a major retrofit after 20 years. As hot rolling sites have lifetimes of 50 years and – in contrast to blast furnaces in the alternative steel making path – still provide retrofit benefits after lifetime expiry (which hinders companies from moving), the share of integrated steel making goes down in this path.

In the BF/BOF path on the other hand integration shares grow up moderately from 60 % to 63 %.

It has to be stressed that integrated capacities give room to save energy but that actual savings depend on existing infrastructure at the sites to get hot steel fast and with little heat transfer from the casting house to the hot rolling mill (s. above). Further on, limited capacity utilization and the need of flexible production can diminish the possibilities for hot charging. So the shown integration shares show only theoretical potentials.

If assuming a medium share of 40 % of hot charging in integrated sites with a specific saving of 0.5 GJ/(t hot rolled steel) there would be actual savings of 2.3 PJ in the "innovative steelmaking path" and 4.8 PJ in the "BAT steelmaking path. With 100 % integration and 40 % hot charging 8 PJ would be possible. This corresponds to 20 % of overall energy use of hot rolling in 2050 a hypothetical case without hot charging.[3]

3. The estimation is based on the use of best available technology in hot rolling as reported in de Lamberterie (2014).

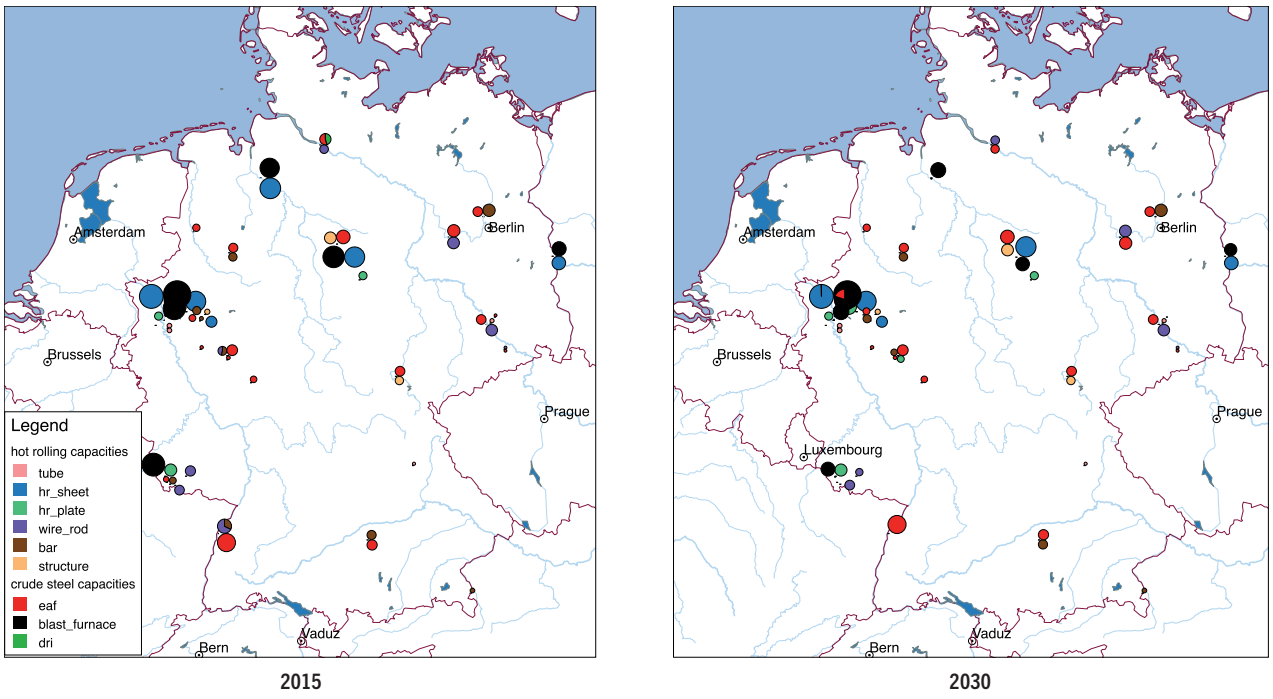


Figure 3. Maps for crude steel making and hot rolling capacities 2015 and 2030.

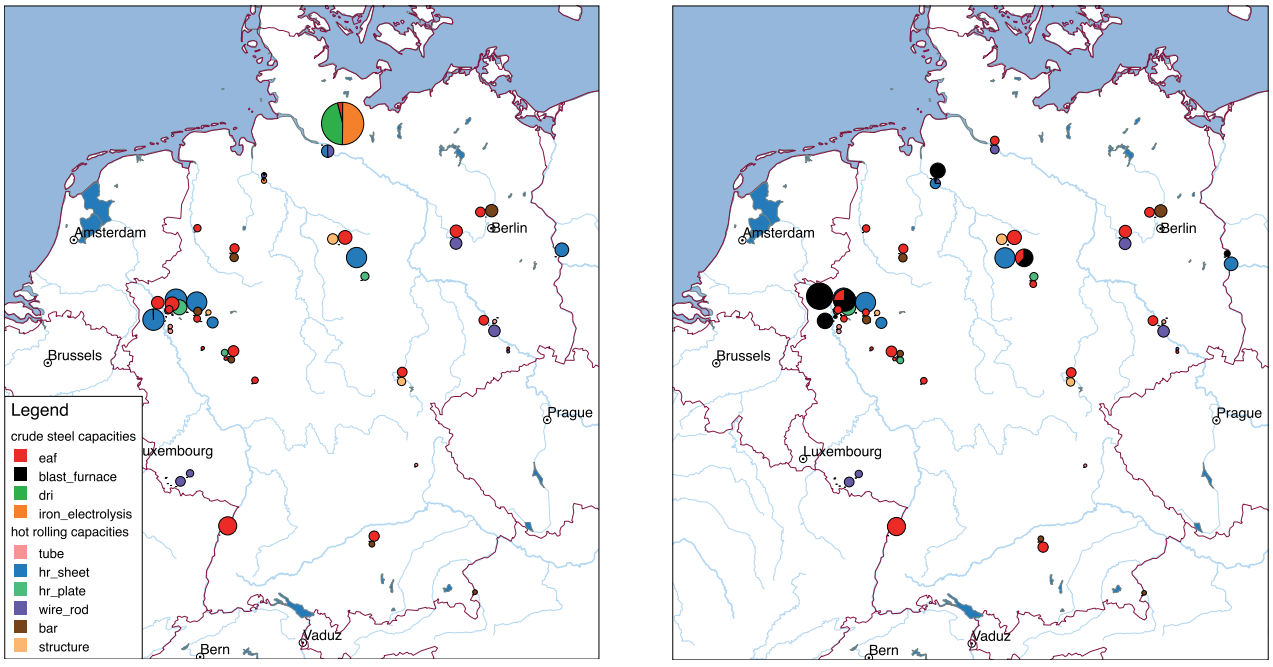


Figure 4. Maps for crude steel making and hot rolling capacities 2050 (two base scenarios).

SENSITIVITY ANALYSIS

A pre-sensitivity analysis (keeping all other parameters of the two base scenarios frozen) showed that natural gas price and revenues from electricity production or the interest rate are no sensitive parameters in the model and variation does not change the results of the model. Considering the coefficients of the target function (given above) this finding is not surprising as the other values of the function (retrofit "benefits" as well as transport costs for coal and iron) dominate the decision. Retrofit of a complete BF/BOF site inhibits a benefit of 368 EUR/yt (net present value). Table 5 gives some selected coefficients of the target function to illustrate the dominance of retrofit and transport costs. However the model results are very sensitive in regard to demand development.

Results presented in the former section showed capacity development in an ideal environment where production of each semi-finished steel product is stable over time. Time series of steel demand however show waves on the one hand and

structural changes on the other hand (Figure 5). Therefore and to test relevance of variance of other parameters a sensitivity analysis was carried out.

To test sensitivity of hot rolled steel production a set of 30 production scenarios with random production values for each of the six semi-finished steel products was created.

The (statistically) expected growth rate for each of the six demand vectors from one scenario year to the next (five years later) is zero with a possible range of ±20 %. So there is a quite great variety of possible demand (and production) projections for each of the six products and overall development. The set of 30 scenarios is therefore too small to give statistically valuable information on sensitivity but it gives qualitative hints on integration shares and geographical spread of capacities shown in the graphs and heat maps below.

Figure 6 shows integration shares in relation to HR steel production level (2050) and in relation to standard deviation over time. Standard deviation of hot rolled steel production over time is defined here not for aggregated production but for each of the six products to provide that negative and positive developments for different products do not level out each other. Therefore moduli of deviations between actual values and expected production values (i.e. the production volume of one period vs. the production volume of the previous period) for each product were summed up each scenario year and taken as a base for the calculation of standard deviation respectively.

Figure 6a shows that in the BF/BOF path integration shares are generally higher if production volume is higher. Additional HR capacities are then built around existing crude steel capacities. Figure 6b gives the hint that in the alternative steelmaking path standard deviation of HR steel production over time is more decisive. It needs ruptures in the production trends to enable higher integration shares here. A midterm decline followed by a recovery would encourage companies to close down factories and built new integrated ones afterwards.

Figure 7 shows integration potentials in the plant dispatch which differs from capacity integration: Not all capacities are actually needed and if integrated sites are preferred to isolated sites in the dispatch the integration share can be higher than in the distribution of capacities. If – on the other hand – integrated sites' capacities exceed market demand the share of integration in dispatch is lower than in capacities.

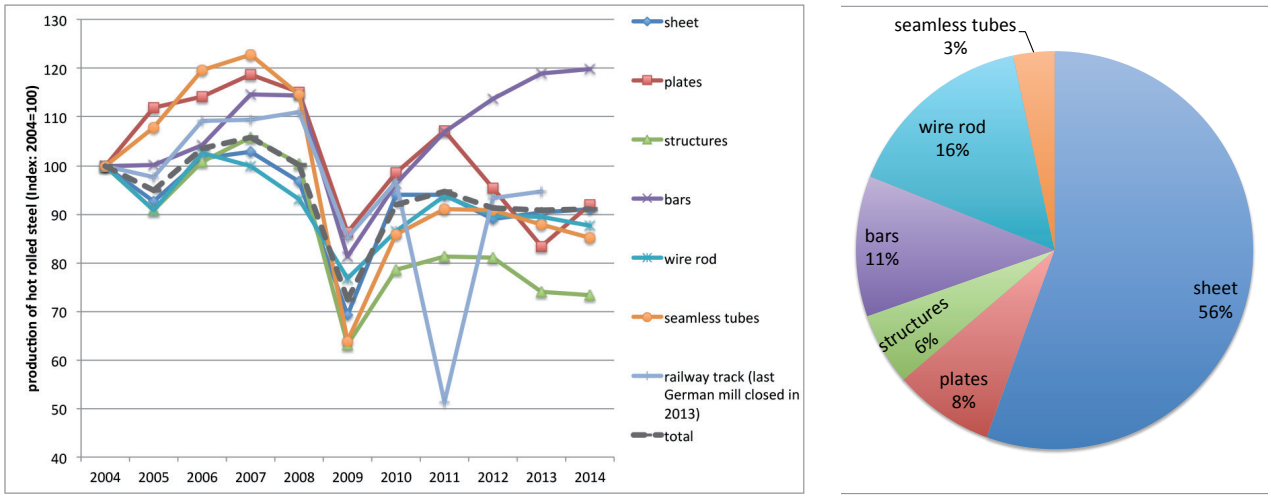
Figure 7 shows that integration potentials in the plant dispatch are distributed analogous between the two technology

Table 5. Selected coefficients of the target function.

	case 1		case 2	
	net present value/(t*a)	selected case	net present value/(t*a)	reference case(s)
Retrofit benefit for a complete BF/BOF site	-368 EUR/yt	retrofit	–	greenfield investment
transport costs*	0 EUR/yt	Hamburg (sea port)	62 EUR/ yt// 80 EUR/ yt// 141 EUR/yt	Duisburg// Salzgitter// Dillingen
benefit of hot charging for a completely integrated production (CS net production = production of HR steel product)	-19 EUR/yt**	hot charging	–	no hot charging

** Only costs for inland transportation regarded.*

*** Only 10 years forecast because of higher uncertainty if both CS and HR mill can be operated at full capacity respectively.*



time series 2004–2014 (index: 2004=100) **hot rolled steel production in 2014 (in total 37.7 mill. tons)**

Figure 5. Production of hot rolled steel products in Germany 2004–2014 [source: World Steel (2016)].

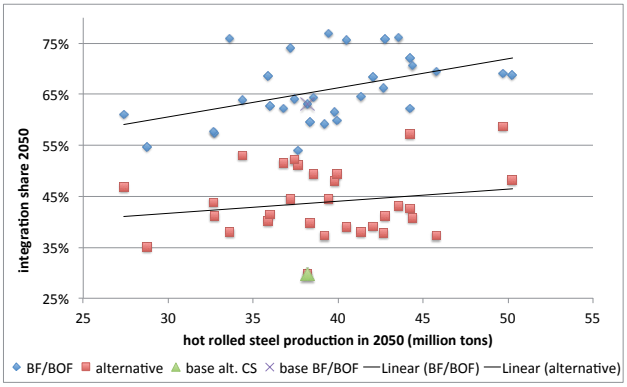


Figure 6a

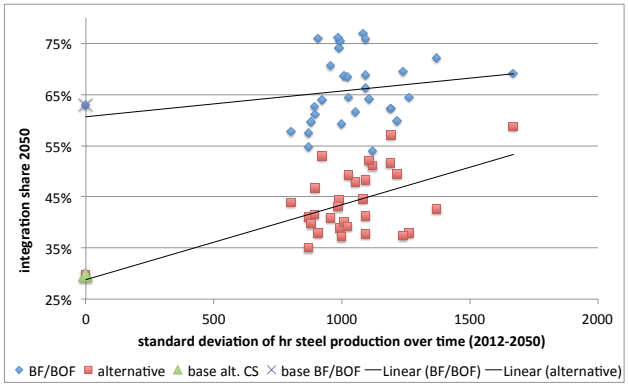


Figure 6b

Figure 6. Integration share as a result of sensitivity analysis.

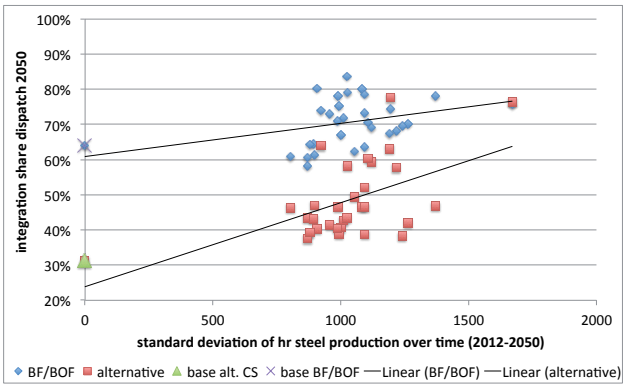


Figure 7. Integration share of plant dispatch (capacity use) in 2050 as a result of sensitivity analysis.

pathways. In the alternative pathway considerable integration shares of 76 % and 78 % (at the level of BF/BOF path integration) are reached if hot rolled sheet demand increases after 2030.

Finally, the heat maps in Figure 8 and 9 show that spatial distribution of capacities proves to be quite robust in the sensitivity analysis: In the alternative pathway capacities shift to the North range ports (Hamburg and Bremen) and EAF capacities are augmented in the Ruhr area (Western Germany). In the BF/BOF path the traditional structure prevails with integrated primary steel and hot rolling (sheet) capacities at the River Rhine and an only low probability to maintain the disintegrated sites at the Saar (near Luxemburg) with their higher transport costs.

Conclusion

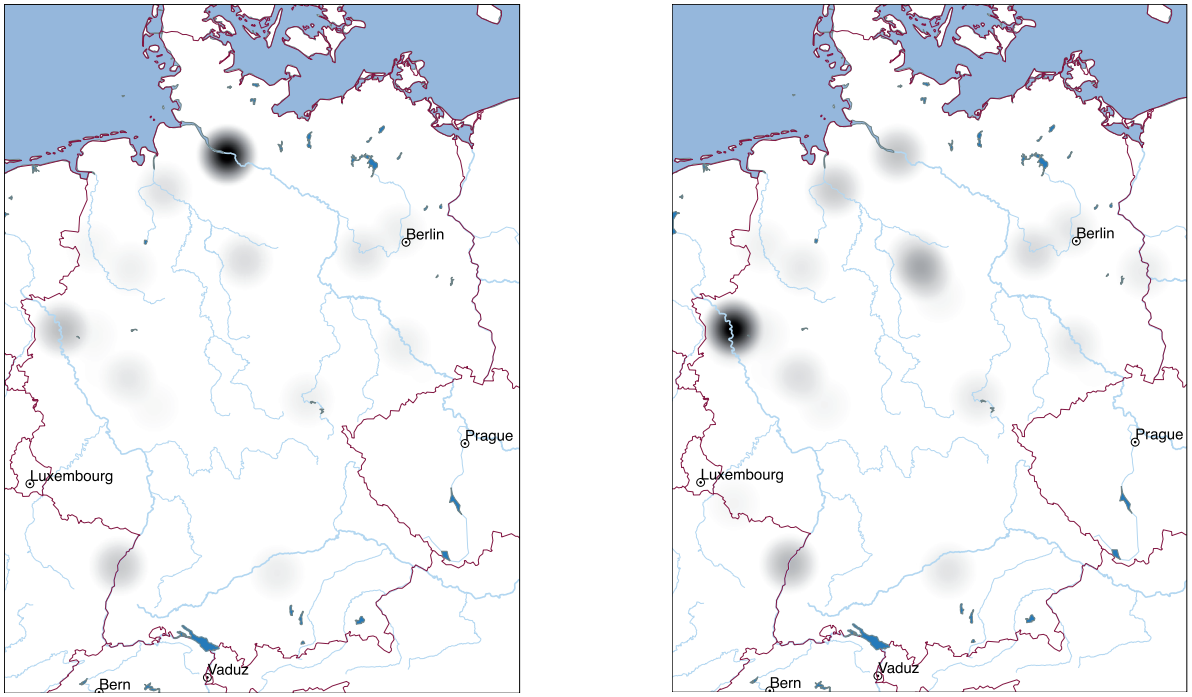
Steel making is one of the major energy consumers in the EU and globally. In spite of high shares of energy in production costs still high savings potentials do exist (see, e.g. Johansson et al. 2011), among others by better integrating steel making and rolling to produce intermediates such as sheets, bars, tubes etc. In Germany – partly due to historical developments integrated steel production is less common than in e.g. China. To appraise the potential of this technology for the future not only different possible technological pathways are crucial but also their probable spatial characteristics. To analyse these, we developed a new type of model, which is not only technologically detailed but also spatially explicit.

Until 2050 two different pathways for German steel production have been analysed. Either, current structures prevail and the conventional BF/BOF technology route will remain dominating the primary steel route, together with a slightly increasing trend toward secondary steel making with electric arc furnaces. Or – if the energy system changes more drastically in coming decades – new technologies with an energetic base on renewable electricity providing green electricity and/or derived gases such as methane or hydrogen such das DRI with renewable methane or hydrogen or electrowinning (electrolysis of iron ore) could be come the predominant technology for primary steel making.

Both scenarios will have significant impacts on the spatial and technological development of German steel making and the efficiency potentials of integrated steel making. While in the conventional scenario BF/BOF capacities may be reallocated again with rolling facilities and by this increase the potential for integration, the alternative scenario will rather reduce the incentives for integration. Several sensitivity analyses show, however, that energy savings due to heat integration are probably not a decisive factor for greenfield investment. Here transport costs could dominate and lead to more steel making at the coast in both scenarios but particularly in the alternative CS. Both scenarios are sensitive on the total share of new greenfield investment compared to retrofitting. Here cyclical trends could play a role as discontinuities would hurt existing sites most and would lead to final closures of existing sites and "open the game" for new greenfield sites.

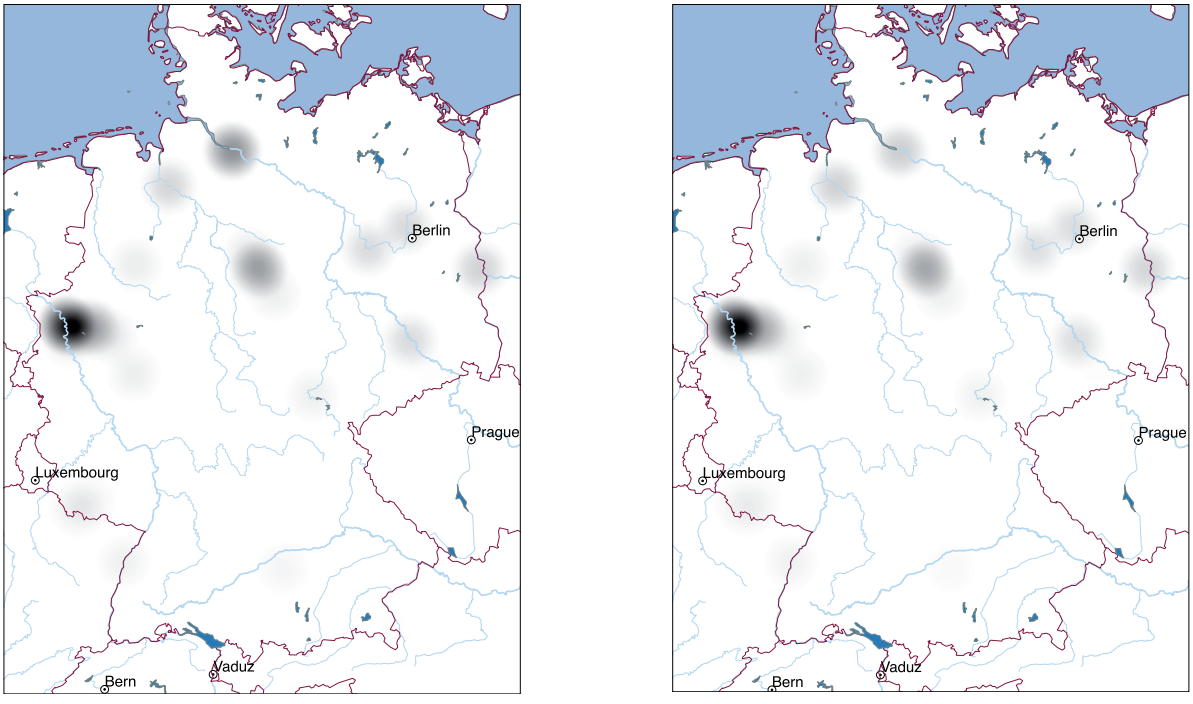
However, these results also point at the limits of the model used. Effects of international competition and potential relocations to sites abroad are not covered. Also the heavy infrastructure requirements (e.g. special port facilities or railways) as well as issues of local acceptance of new CS facilities – which in turn would favour retrofitting strategies against greenfield investments – are not covered.

The model could be extended to the EU level. Doing so could bring in a number of new insights and reflect that there is a common steel (and scrap) market in Europe. However, modelling would have to take spatial distribution of final steel consumption into account. Bulk material transport from seaports to the inland are often quite cheap especially if inland waterways can be used. Finished steel products on the other hand are often transported



alternative steelmaking path BF/BOF steelmaking path

Figure 8. Heat maps 2050 for crude steel making (thirty demand scenarios).



alternative steelmaking path BF/BOF steelmaking path

Figure 9. Heat maps 2050 for hot rolling (thirty demand scenarios).

by truck to customers because of smaller individual sale volumes, so distances are more relevant – both in economic and in ecological terms. So if we see a concentration of CS production and hot rolling at sea ports in our model results that should be a valid result for the German market where all regions are within a 1,000 km range to a seaport, but probably not valid for Eastern Europe where customers are more far away from seaports.

Finally the influences of decarbonisation strategies could be reflected more in detail. From a technological point of view this could be on the one hand availability and cost differentials of RES electricity and derived gases and on the other hand CCS-infrastructures. Both could be taken into account in an updated model. Although the model used here is still limited our first analyses show, that the analysis of energy efficiency potentials in steel making can be significantly improved by using spatially explicit modelling.

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