Steel manufacturing clusters in a hydrogen economy – simulation of changes in location and vertical integration of steel production in North-Western Europe

Supplementary Material

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1 Documentation of the optimisation model applied

A linear programming (LP) optimization procedure in R (lpSolve[1]) was used to solve the optimization problem, i.e. discrete variables have to be used.

1.1 Microeconomic optimization procedure

A linear optimisation function is used, which has a general form like follows:

$$x_0 = f_0(x_1 \times a_1 + x_2 \times a_2 + \cdots + x_n \times a_n) \rightarrow Max!\,(Min!)$$

where x_0 represents the target value to be maximised or minimised.

The target function requires an additional set of m constraints. Each of the m constraints has a general form like follows

$$x_1 \times b_1 + x_2 \times b_2 + \cdots x_n \times b_n > c_m$$

Formula 1 represents the actual target function of the economic optimization procedure, which was used for the modelling. The variables of the functions (x_n) are bolded and the respective coefficients (a_n) are given in brackets. The invest function is repeated for each of the i=84 sites. The target value to be minimized represents the net present value of the sum of all investments in one five-year-period. In Box 1 the terms used in the formula are defined. The set of constraints (shown in Box 2) consists of 41 site-specific constraints (repeated for each of the 84 sites) and ten non-site-specific ones, making up to a total of 3454 constraints.

Formula 1: target function of the optimisation procedure

$$NPV = \sum_{i=1}^{84}\Big(\boldsymbol{CI_{EAF_i}} \times \Big(SI_{EAF} + \Big(SEU_{EAF} \times P_{el_i} + \frac{1}{STC_{iron_i}}\Big) \times AF_1\Big) + \boldsymbol{RPU_{EAF_i}} \times (SSR_{EAF}) + \boldsymbol{CI_{BF_i}} \times (SI_{BF} + (STC_{iron_i} + STC_{coal_i} + SEU_{BF} \times P_{el_i}) \times AF_1) + \boldsymbol{RPU_{BF_i}} \times (SSR_{BF}) + \boldsymbol{PPU_i} \times (SSP_i) + \boldsymbol{CI_{DRI}} \times (SI_{DRI} + (STC_{iron} + SEU_{DRI} \times P_{el_i}) \times AF_1) + \boldsymbol{RPU_{DRI_i}} \times (SSR_{DRI}) + \boldsymbol{CI_{HR_{1_i}}} \times (SI_{HR_1} \times LF_{HR}) + \boldsymbol{RPU_{HR_{1_i}}} \times (SSR_{HR_1}) + \ldots + \boldsymbol{CI_{HR_{7_i}}} \times (SI_{HR_7}) + \boldsymbol{RPU_{HR_{7_i}}} \times (SSR_{HR_7}) + \boldsymbol{IPU_{CS_i}} \times (SSI \times LF_{HR} \times AF_2) + \boldsymbol{IPU_{HR_i}} \times (SSI \times LF_{CS} \times AF_2) + \boldsymbol{IPU_{parallel_i}} \times (SSI \times LF_{HR} \times AF_2) + \boldsymbol{SGI_{BF_i}} \times (SSGIS \times LF_{HR} \times AF_2) + \boldsymbol{SGI_{HR_i}} \times (SSGIS \times LF_{CS} \times AF_2) + \boldsymbol{SGI_{parallel_i}} \times (SSGIS \times LF_{HR} \times AF_2) + \boldsymbol{PSIPU_{PS_i}} \times (SSI \times LF_{HR} \times AF_2) + \boldsymbol{PSIPU_{sheet_i}} \times (SSI \times LF_{CS} \times AF_2) + \boldsymbol{PSIPU_{parallel_i}} \times (SSI \times LF_{HR} \times AF_2) + \boldsymbol{PIA_i} \times (SV\_PIA)\Big)$$

Box 1: Definitions for terms used in the target function and in the constraints

NPV = total net present value of invest in crude steel and hot rolling capacities, plus transport costs and operational costs, but only those parts, that differ in regard to the site specifications, opex that are equal at all sites are not considered

SI = specific investment costs for crude steel or hot rolling capacities (in EUR/(yt))

SEU = specific electricity use

[1] See https://cran.r-project.org/web/packages/lpSolve/lpSolve.pdf for a documentation of the R package.

CI = amount of capacity investment in the five-year-period (in capacity of metric tons/a=yt)

$\mathbf{P_{el_i}}$ = electricity purchase price at site i

$\mathbf{STC_{iron_i}}$= specific transport costs of iron ore transport to site i (per tonne of iron)

$\mathbf{STC_{coal_i}}$= specific transport costs of coal transport to site i (per tonne of coal)

RPU = retrofit potential used (yt)

SSR = specific saving if retrofit is used (in -EUR/(yt), represented by negative figures

PPU = existing periphery of the BF/BOF route which is integrated by BF investment (yt); weighted according to the existing capacities of coke ovens, sinter plants and blast oxygen furnaces at a site and their specific investment costs respectively

SSP = specific saving by integrating existing BF periphery (in -EUR/t), represented by negative figures; weighted according to the existing capacities of coke ovens, sinter plants and blast oxygen furnaces at a site and their specific investment costs respectively

IPU = new (marginal) integration potential used; i.e. hot rolling capacities which are integrated by additional CS capacity investment (yt) or vice versa or *parallel* investment in both crude steel and hot rolling capacities

SSI = specific saving by vertical integration through savings in transhipment and hot charging (in -EUR/t); net present value (time horizon: 10 years), represented by negative figures

$\mathbf{AF_1}$ = annuity factor for annual costs or income connected to an investment which are estimated to last for 20 years

$\mathbf{AF_2}$ = annuity factor for annual costs or income connected to an investment which are estimated to last for 10 years (savings from the integration of the two different assets are only calculated for a period of 10 years as the market risk of loosing one of the assets is higher than if only considering one asset)

SGI = amount of additional (marginal) capacity integration between the blast furnace route and hot rolling (yt)

SSGIS = specific savings by steel gas use in hot rolling compared to natural gas use (in -EUR/t), represented by negative figures

PSIPU = amount of additional (marginal) capacity integration between primary steel production capacity and hot rolling capacity[2] (yt)

PIAP = amount of primary steel infrastructure assets at a site, i.e. transport and loading as well as storage infrastructure for iron ore that have been set free by the end of lifetime of primary steel production assets

PIA = amount of PIAP, which is reused when reinvesting in new primary steel capacities or retrofitting

SV_PIA = Specific value of the primary steel infrastructure

LF = typical load factor assumed for an investment

RP = retrofit potential (capacity of metric tons/a=yt)[**)]

PP = periphery integration potential, i.e. "free" coke oven, sinter and BOF capacities (in yt)[*)]

HRIP = hot rolling integration potential, i.e. "free" hot rolling capacities (in yt)[*)]

CSIP = crude steel integration potential, i.e. "free" crude steel capacities (in yt)[*)]

SGIP = steel gas integration potential, either $SGIP_{HR}$ for hot rolling capacities not yet integrated or $SGIP_{BF}$ for capacities of the blast furnace route not yet integrated[*)]

$\mathbf{PSIP_{PS}}$ = primary steel integration potential, i.e. "free" primary steel capacities (in yt), not integrated with hot rolling sheet capacities yet[*)]

$\mathbf{PSIP_{sheet}}$ = hot rolled sheet integration potential, i.e. "free" hot rolling sheet capacities (in yt), not integrated with primary steel capacities yet[*)]

[2] The savings by PSIPU are actually double counted with the savings by IPU. However, as these additional savings are not high enough to cause a negative NPV of the investment and thus do not induce additional investment but only change the relative cost "position" of primary steel sites compared to secondary steel sites when integrating with the hot rolling of sheet this procedure was used. To calculate the actual amount of savings by IPU the integration of secondary production with hot rolled sheet should not get a "premium" because sheet production from scrap is not common as sheet requires a higher steel purity than other sorts. PSIPU compensates for this and ensures the correct cost position of sites in regard to integration of hot rolled sheet.

CN = capacity need (in yt); CN_{EAF} expresses investment need in secondary steel making capacities, CN_{PS} expresses investment need in primary steel making and CN_{HR_k} expresses the investment need in hot rolling capacity of hot rolling mill of kind k (with seven different hot rolling mill capacity kinds)

The following **indices** are used:

CS=crude steel

HR=hot rolling

PS=primary steel

sheet=hot rolled sheet

BF=blast furnace route

DRI=DRI route

EAF=secondary steel route

Additional **running indices:**

i is used for sites and runs from 1 to 84

j is used for all different kinds of capacities, i.e. three steel making and seven hot rolling mill kinds (1 to 10)

k is used for all kinds of hot rolling mills (1 to 7)

*) a ten-year-forecast at the site level is used here and capacities are weighted, e.g. if some capacity to be integrated has a remaining lifetime of only five years then only 50% of it are taken into account

**) retrofit potential is defined by the amount of capacities that reached the end of lifetime in the prior 5-year-period

Box 2: Constraints for the linear optimisation

$RPU_{j_i} \leq RP_{j_i}$ *(1)*
$PPU_i \leq PP_i$ *(2)*
$IPU_{CS_i} \leq HRIP_i$ *(3)*
$IPU_{HR_i} \leq CSIP_i$ *(4)*
$SGI_{BF_i} \leq SGIP_{HR_i}$ (5)
$SGI_{HR_i} \leq SGIP_{BF_i}$ (6)
$CI_{j_i} \geq RPU_{j_i}$ (7)
$for\ hot\ rolling\ mill\ kinds\ k = 1\ to\ 7: \sum_{k=1}^{7} CI_{HR_{k_i}} \geq IPU_{CS_i}$ (8)
$and\ \sum_{k=1}^{7} CI_{HR_{k_i}} \geq IPU_{CS_i} + IPU_{parallel_i}$ (9)
$CI_{EAF_i} + CI_{BF_i} + CI_{DRI_i} \geq IPU_{HR_i}$ (10)
$CI_{EAF_i} + CI_{BF_i} + CI_{DRI_i} \geq IPU_{HR_i} + IPU_{parallel_i}$ (11)
$for\ hot\ rolling\ mill\ kinds\ k = 1\ to\ 7: \sum_{k=1}^{7} CI_{HR_{k_i}} \geq SGI_{BF_i}$ (12)
$and\ \sum_{k=1}^{7} CI_{HR_{k_i}} \geq SGI_{BF_i} + SGI_{parallel_i}$ (13)
$CI_{BF_i} \geq SGI_{HR_i}$ (14)
$CI_{BF_i} \geq SGI_{HR_i} + SGI_{parallel_i}$ (15)
$PSIPU_{PS_i} \leq PSIP_{sheet_i}$ (16)
$PSIPU_{sheet_i} \leq PSIP_{PS_i}$ (17)
$CI_{HR_{sheet_i}} \geq PSIPU_{PS_i}$ (18)
$CI_{HR_{sheet_i}} \geq PSIPU_{PS_i} + PSIPU_{parallel_i}$ (19)
$CI_{BF_i} + CI_{DRI_i} \geq PSIPU_{HR_i}$ (20)
$CI_{BF_i} + CI_{DRI_i} \geq PSIPU_{HR_i} + PSIPU_{parallel_i}$ (21)
$CI_{BF_i} + CI_{DRI_i} \geq \mathrm{PIA}_i$ (22)
$\mathrm{PIA}_i \leq PIAP_i$ (23)

For the sum of capacity investments in all 84 sites the following constraints apply:
$\sum_{i=1}^{84} CI_{HR_{k_i}} \geq CN_{HR_k}$ (24)
$\sum_{i=1}^{84} CI_{EAF_i} \geq CN_{EAF}$ (25)
$\sum_{i=1}^{84} (CI_{BF_i} + CI_{DRI_i}) \geq CN_{PS}$ (26)

Finally, invest in certain primary steel making technologies is prohibited by
$\sum_{i=1}^{84} CI_{BF_i} \leq 0$ or $\sum_{i=1}^{84} CI_{DRI_i} \leq 0$ (27)

1.2 Parameters used in the optimization model

Table 1. 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	8.0	own assumption
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 H-DR (&EAF)	EUR/(t cap*a)	-	874	Fischedick et al. (2014), based on Wörtler et al. (2011)
specific invest HR	EUR/(t cap*a)	180	180	own assumption based on different sources
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 DRI	%	50	50	own assumption
saving retrofit HR	%	50	75	own assumption
specific coal use	t/t hot iron	0.68	0.68	aggregated EU values for BF, sinter plants and coke ovens (JRC 2012)
specific iron ore use	t/t hot 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	5'000	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).

2 Analysis of NWE production stock

Table 2. Overview on iron & steel capacities in North-western Europe [source: authors' enquiries, production volumes according to #World Steel (2016)]

		number of sites	number of plants	capacity (million tons/y)	capacity utilization (2015)	age (mean)*)
primary steel making	Coke oven	10	15	16	not reported	30
	Sinter plant	10	15	52	not reported	44
	Blast furnace (BF)	12	28	57	85%	36
	Basic oxygen furnace	11	26	58	88%	32
	DRI	1	1	0.6	92%	44
secondary (scrap) steel making	Electric arc furnace (EAF)**)	40	46	30	75%	28
hot rolling (HR)	Sheet	14	17	58	77%	44
	Heavy plate	8	8	7	60%	34
	Structure	7	8	5	73%	49
	Bar	20	20	11	59%	34
	Wire rod	14	15	11	81%	36
	Railway track	1	1	0.3	130%	123
	Seamless tube	5	5	1	76%	63

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

**) Including EAF at the Hamburg DRI site.

84 individual sites were accounted in the database (including sites which have been closed just recently).

3 Documentation of additional results

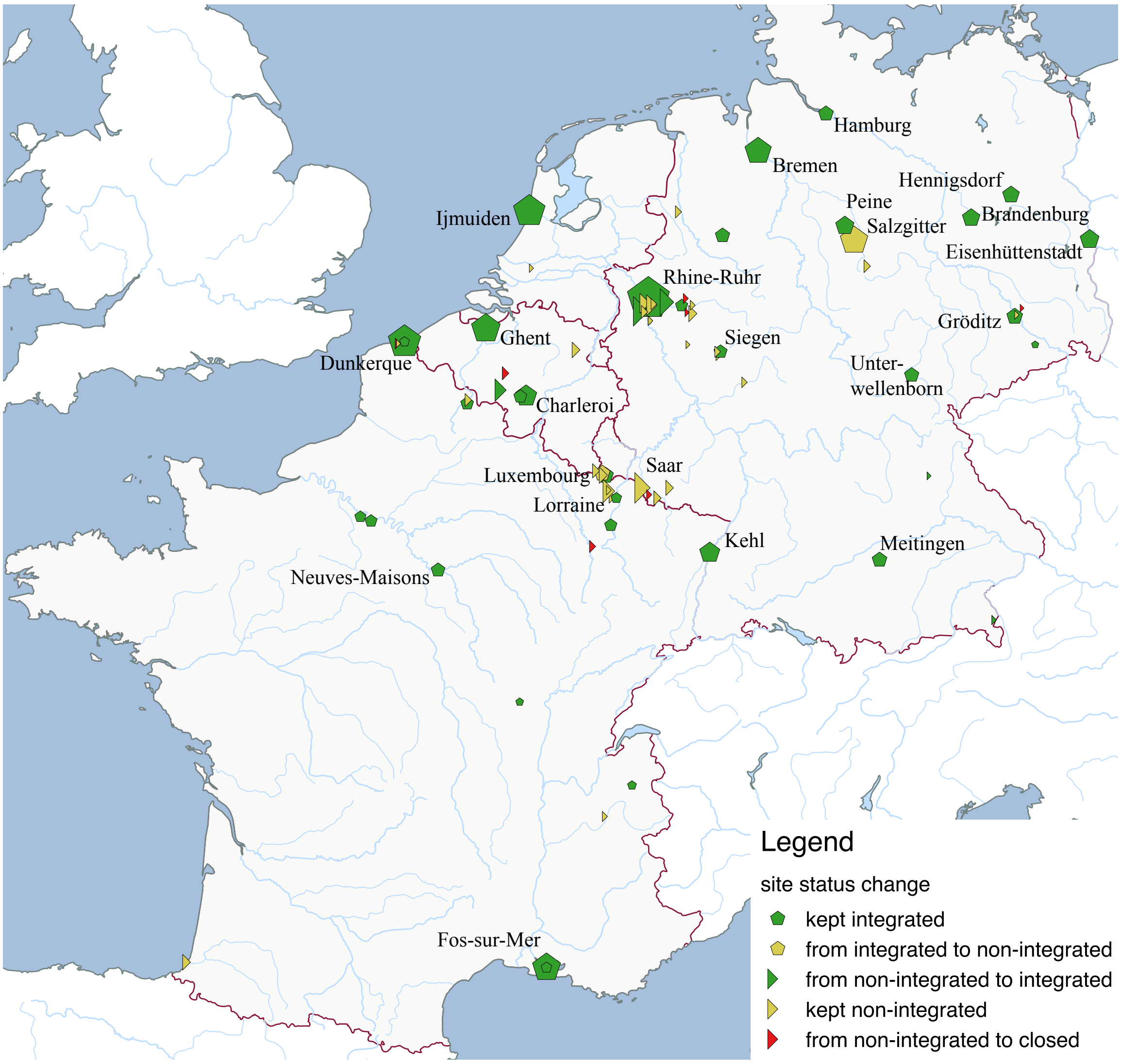

Figure 1. Map on site status change from 2015 to 2050 in the base electrification scenario
Source: own analysis.

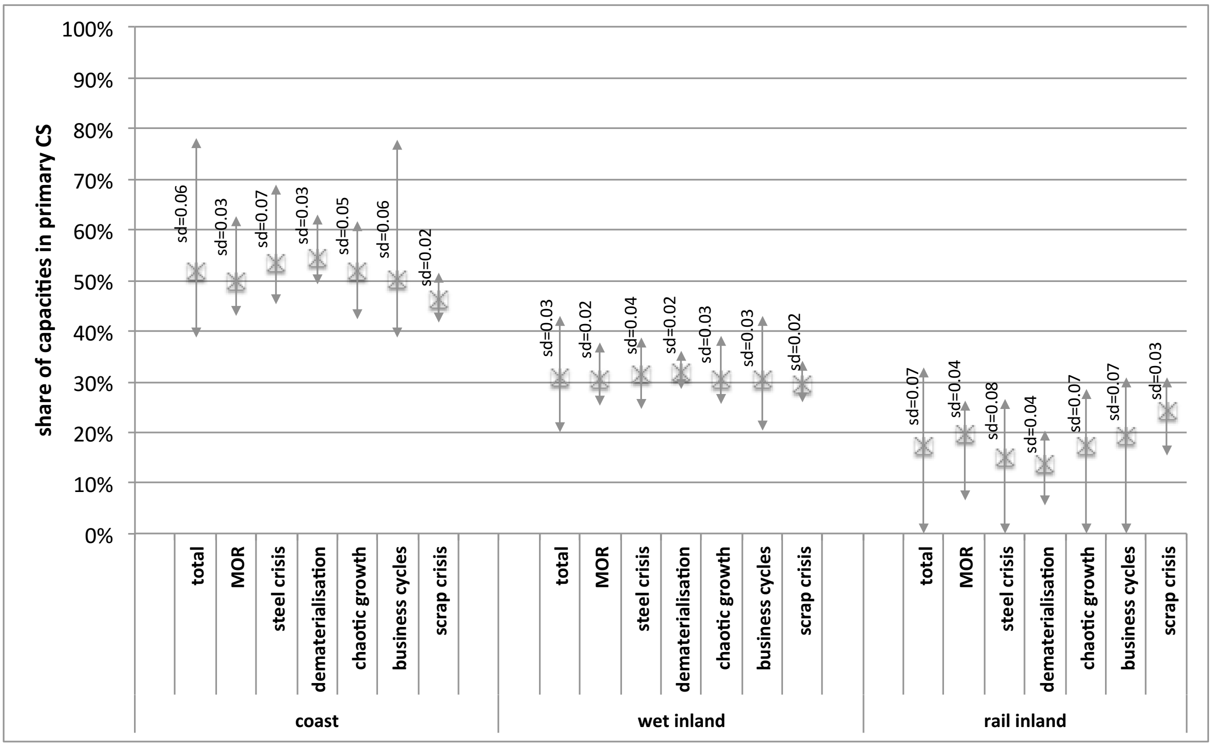

Figure 2. mean share, maximum and minimum as well as standard deviation of primary steelmaking capacities 2050 in regard to site type of different classes (MC analysis of electrification case)

4 Additional literature in the supplementary material

Prognos/EWI/GWS (2014): Entwicklung der Energiemärkte – Energiereferenzprognose. Final report. Study on behalf of the German Federal Ministry for Economics and Technology. Basel/Köln/Osnabrück.

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IEA (2010): IEA Energy Technology Systems Analysis Programme (IEA ETSAP). Combined Heat and Power. (May 2010). www.iea-etsap.org

JRC (2012): Best Available Techniques (BAT). Reference Document for Iron and Steel Production. Seville.