PEER-REVIEWED PAPER

Re-industrialisation and low carbon economy – can they go together? Results from transdisciplinary scenarios for energy intensive industries

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Abstract
This paper draws upon an extensive transdisciplinary scenario development in the context of the stakeholder oriented preparation of the climate protection plan of the German federal state North Rhine-Westphalia, which is home to the most important heavy industry cluster in Europe. In that context we developed differentiated bottom up climate change mitigation strategies and scenarios for the major energy intensive industries aluminium, iron and steel, cement, lime, paper and steam cracker for olefin production together with representatives of industry as well as society.

We combine rather optimistic assumptions of an 1.2 % annual growth rate of industrial value added until 2050 with three different technological pathways in order to analyse which technologies would be needed to achieve the Commission's vision of a re-industrialisation simultaneously with the long term targets of its Low Carbon Economy Roadmap and which role energy efficiency has to play in this context:

1. In the first scenario current best available technologies help increase energy efficiency but are overcompensated by economic growth.
2. In the second scenario break-through technologies for a decarbonisation of industry are assumed, which lead to a fuel shift towards electricity and hydrogen produced by excess renewable electricity.
3. In the third scenario, CO_2 capture and storage for steel, cement and lime plants is applied alternatively. This strategy leads to higher energy demand but achieves the highest mitigation levels.

All pathways are coupled with an ambitious renewable electricity scenario within an integrated energy system model for Germany where power plant use and primary energy consumption are modelled depending on electricity and hydrogen demand with a time resolution of one hour.

Our results indicate the importance of successful development and implementation of break-through technologies in industry if significant growth and climate mitigation are to be achieved together. They, however, also show that technological potentials have their limitations. This means that on a global scale limiting production and consumption of basic materials could become critical for a low carbon society.

Introduction
North Rhine-Westphalia (NRW) is the most populous and densely populated state in Germany with 18 million inhabitants. Backbones of its economic structure is the energy sector with extensive hard coal and lignite mining, power production and a huge energy-intensive industry. About 30 % of Germany's electricity supply is produced in NRW (70 % coal-based, 90 % fossil), while its industrial electricity demand amounts to 40 %. About 1/3 of German greenhouse gas (GHG) emissions (~300 Mio. t/a) come from this region, which is about 6 % to 7 % of the entire EU GHG emissions.

Due to this energy-based industry structure, the state is key for meeting national and European climate targets. If it does not succeed in reducing its emissions considerably, it is unlikely that Germany and Europe will succeed in meeting the targets formulated by the European commission roadmap (EC 2011). This roadmap urges to reduce GHG emissions by 79 % in 2050 compared to 1990. The targets for 2030 are 40–44 %. For the industry sector, the reduction targets are even more ambitious with 83–87 % by 2050 with regard to 1990. The assumed economic development for the EU-27 economy leads to a challenging decoupling of resource use and emissions.

Within this European target corridor, the NRW state parliament (Landtag) concluded a climate protection law which stipulates Greenhouse gas reductions in North Rhine-Westphalia of at least 25 % by 2020 and at least 80 % by 2050 (vs. 1990) and the development of a climate protection plan with strong stakeholder participation. Key elements of this plan are a specification of the climate protection goals temporally, sectoral and regionally. In line with that, strategies and measures are discussed and developed to achieve the goals outlined in the Climate Protection Law.

This paper first describes the transdisciplinary process of interactive stakeholder based scenario development within the climate protection plan development (methodology). The basic assumptions taken in the different scenarios are presented after that in detail, followed by a discussion of results for the five main energy intensive industries, which are responsible for almost 40 % of industrial GHG emissions. The paper closes with conclusions for industry and policy makers.

Methodology

The methodology used is a combination of an iterative stakeholder process to formulate core assumptions of scenarios, which were jointly developed and intensively discussed. For the quantitative simulation of the scenarios an integrated technical energy system model is used.

STAKEHOLDER BASED SCENARIO DEVELOPMENT

According to the before mentioned state climate protection law a climate protection plan is to be developed by full participation of stakeholders in a wide-scale dialogue and participation process[1]. For a first phase of the process stakeholder working groups have been convened for each of the six main GHG emitting sectors: energy conversion, industry, buildings and businesses, transport, agriculture and private households. The groups were supported by moderators and scientists who were responsible in the framework of a transdisciplinary process for refining the group's proposals and for developing and calculating the scenarios. The objective of each group was to develop a set of medium and long-term strategies to reduce GHG emissions – which were then combined to one or more scenarios for that sector. Based on this the groups proposed and evaluated short and medium term measures deemed necessary to implement the strategies and scenarios for their sector. By this approach we try to improve on the consideration of the "specific social and political conditions under which the scenarios may likely unfold" by supplementing qualitative analyses with quantitative scenarios and by considering explicitly relevant "short-term policies and actions" (Nielsen & Karlsson 2007). As the stakeholders themselves were to decide on important design criteria as well as on the results as such this can be called a transdisciplinary process with the highest intensity of stakeholder involvement (cp. Brandt et al. 2013) The sectoral scenarios by all six groups were finally combined to a set of combined scenarios, which are going to be used by the government as a basis for the formulation of the climate protection plan.

In this paper, we draw upon on the discussions and assumptions made by the stakeholders from the industry sector working group and show results from the energy scenarios developed for this sector. This group comprised about 40 stakeholders, most of them being representatives of companies from energy intensive industries, together with representatives from industries associations, trade unions, chambers of commerce, environment/conservation and consumer organisations, associations of municipalities, academia and others.

For the interactive scenario building process the energy system simulation model described below was used, as it is well suited for such a transdisciplinary process. The detailed technical representation of processes in the model enable for in depth discussions with representatives of different industries in order to check assumptions made from literature and also help to make the scenarios transparent and understandable by the stakeholders. Because of the stepwise bottom-up process employed the scenarios do not follow a target oriented back-casting approach but rather exploratively try to identify which effects strategies can have that the stakeholders could jointly imagine to be realistic (cp. Nielsen & Karlsson 2007, 304).

ENERGY SYSTEM SIMULATION MODEL

Following the categorization of van Beek (1999)[2] the model applied can be classified as a simulation model using a bottom-up approach with a very detailed representation of energy system technologies and a low degree of endogenization, i.e. many parameters can be changed by bringing in stakeholders' knowledge on certain sectoral technologies. As a bottom-up energy system model it is focussed on unveiling existing energy efficiency and GHG mitigation potentials rather predicting the future (cp. Hourcade et al. 1995).

Other parts of the economy (outside the energy system) are not represented in the model. Geographically NRW's energy demand sectors are covered in detail, whereas the rest of Germany is represented on more aggregate levels apart from power plants, which are modelled in a high resolution for whole Germany. Figure 1 gives an overview on the model architecture with a focus on the industry modules.

The energy and GHG flow model WISEE-ESM NRW[3] serves as a database for all relevant data. In its industry-module[4] more

1. This process was started in spring 2012. A first phase focussing on 6 stakeholder working groups lasted from summer 2012 to winter 2013. A second phase of wider participation is taking place in the first half of 2014. Based on the results from both phases the government is going to draft the plan in the second half of 2014.

2. Van Beek's classification is based on other (earlier) literature cited there.

3. WISEE is an acronym for Wuppertal Institute System Model Architecture for Energy and Emission Scenarios. "ESM" stands for Energy System Simulation Model.

4. Other sector modules are for transport, services and households.

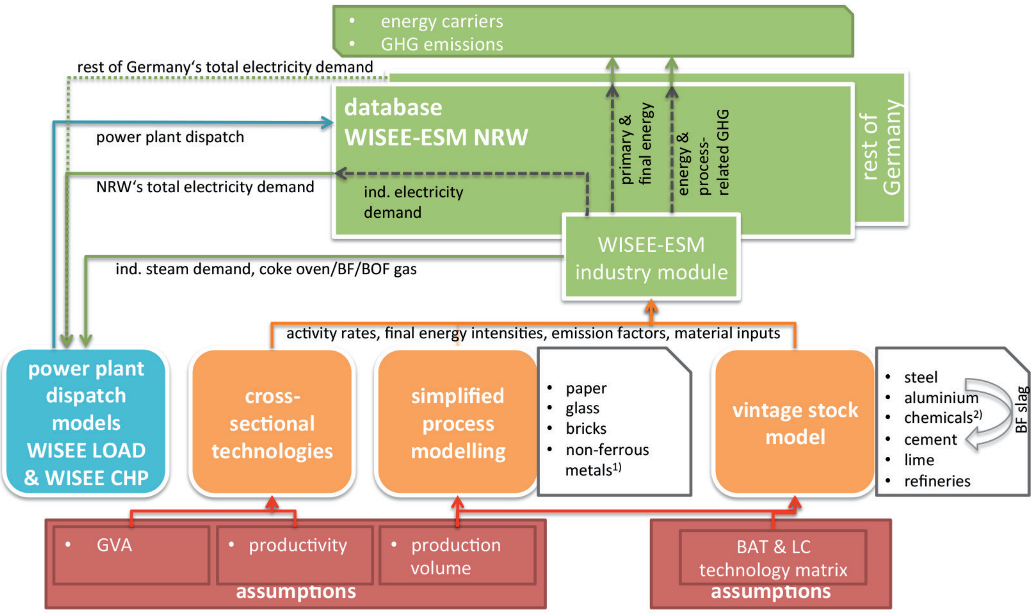

Figure 1. Overview on the WISEE model system (industry focus). Source: Wuppertal Institute.

1) other than aluminium

2) selected base chemicals like ethylene, ammonia, chlorine etc.

Table 1. Share of selected production processes in total CO_2 emissions of industry branches (excl. industrial CHP, CO_2 emissions of electricity and heat demand according to German mix). Source: ETS data, own calculations.

Industry branches	Selected production processes	CO_2 share of selected process in branch (2010)	CO_2 share of selected process in total industry (2010)
iron & steel	primary steel production	79 %	20 %
non-ferrous metals	aluminium production[1)]	35 %	2 %
non-metallic minerals (excl. glass industry)	cement production[2)]	51 %	6 %
chemicals and pharmaceuticals	ethylene production	21 %	6 %
paper & printing	paper production	84 %	3 %
total industry			38 %

1) incl. ingot casting

2) incl. cement grinding

than 20 energy intensive industrial production processes are described with all relevant input and output flows, together with various future technology options. Based on these the flow model calculates energy demand by multiplication of an activity value (e.g. steel production or GVA of an industry) with an energy intensity value. Energy related emissions are calculated by multiplication of energy demand by energy carrier with the respective emission factor, process-related emissions on the base of activity rates (e.g. anode use in the aluminium industry or lime use in steel production) and technology-specific emission factors.

The parameter time series of energy intensities are determined bottom up for every selected special production process and for cross-cutting technologies by each industrial branch in several sub-models, either using vintage stock models for products where data was available for all major plants or as aggregated process modelling (see Figure 1).

Although the whole industry was modelled we focus here on core processes of major heavy industries (aluminium, iron and steel, cement, paper and steam crackers for olefine production), which comprise 38 % of industrial GHG emissions including indirect emissions of electricity and CHP-steam use. Their share of direct emissions from fuel use (excl. CHP fuel use) is even higher (47 %).

For the five selected processes energy efficiency can be analysed and modelled on the basis of individual energy intensive processes representing physical production (instead of monetary units).

Vintage stock models

Large scale energy intensive industrial processes like the processes we selected for the paper at hand are represented in the sub-models by vintage stock models accounting for actual single production stocks with their specific age, capacity and efficiency using ETS data and further information from emission reporting.[5]

Depending on the scenario year a technology matrix provides assumptions for the specifications of new investments or replacements (lifetime, efficiency, energy carriers). Table 2 gives an overview on the respective assumptions used for the scenarios. Industry stakeholders agreed with the assumptions on best available technologies (BAT), which are proven and economically viable. Low Carbon (LC) technologies were chosen by the authors in agreement with stakeholders of civil society. Industry stakeholders mostly approved technical assumptions. The CCS scenario was not considered in the process, so the assumptions on efficiencies and penetration rates for respective technologies were derived from literature by the authors and were not approved by stakeholders.

Energy intensity and activity rate are the crucial parameters to calculate the overall energy flow model represented in the WISEE-ESM. They are modelled in the vintage stock model for each scenario year.

I_{ti} is defined as energy intensity I of technology i (e.g. blast furnaces in NRW) in the year t. Activity rate A_{ti} is defined as the production volume of technology i in the year t.

Energy intensity is the result of energy use in relation to production volume:

$$I_{ti} = \frac{\sum_j E_{tij}}{\sum_j A_{tij}} \tag{1}$$

with E_{tij} as final energy demand of specific production facility j (e.g. single blast furnace) in the year t and A_{tij} as production volume of the respective facility j.

$$\sum_j A_{tij}$$

is then the yearly production volume of technology i in the year t. If actual stock was run with different fuels respective shares were regarded for the existing stock and fed in the database. Each single stock j is accounted if the typical lifetime l_i of stocks of technology i is not exceeded:

$$l_i < t - b_j \tag{2}$$

with b_j as the start-up date of facility j. If actual total capacity

$$\sum_{j=1}^{n} C_{ij}$$

(regarding fade outs of old facilities) does not suffice to cover the given production volume in the year t_1, facility stock is extended by a new facility j_{n+1} with a capacity defined as

$$C_{ij_{n+1}} = A_{t1i} - \sum_{j=1}^{n} C_{ij} \tag{3}$$

Specific energy demand of facility j_{n+1} is extracted from the technology matrix (Table 2).

Power plant dispatch model

Electricity supply is simulated in the detailed power plant dispatch models WISEE LOAD and WISEE CHP which use electricity and CHP-heat demand from all sectors of the whole German energy system. Electricity and (CHP-) heat demand is broken down to a load profile with hourly resolution for the whole year and power plant dispatch is modelled for every hour of the year via rolling time horizons, i.e. power plant dispatch is optimized with full knowledge about the next day's demand and meteorological data.

The model results for the scenario LC are presented in Table 3, we used the resulting emission factors to calculate indirect emissions of industrial electricity and CHP heat consumption.

Assumptions for economic growth and technological development in industry

This section provides an overview of basic assumptions made for the scenarios of the (energy intensive) industry in NRW presented here. First, the industrial growth pathway is discussed in the framework of a range of assumptions developed together with the stakeholders. Second, three different technological pathways are described, two of which reflect the assumptions concluded by the working group. The third scenario additionally sketches a CCS-strategy for industry, which was not approved by the stakeholders.

PATHWAY FOR INDUSTRIAL ECONOMIC GROWTH

For North-Rhine Westphalia, it is assumed that the domestic energy intensive industry will defend its global competitiveness. The on-going structural change in economy is expected to move forward with moderate speed. Background for the estimates of economic development in industry are the assumptions made for the current Federal Governments energy concept (BMWi 2010) and an outlook until 2030 by the German chemical industry (VCI and Prognos 2013). Based on downscaling these national level studies to the specific industrial structure of the state, three growth pathways for industry development in NRW are estimated, leading to different levels of gross value added in 2050 (see Figure 2[6]):

- 0.6 %/a (2010 to 2050): assumed annual growth of industrial value added until 2050 based on (BMWi 2010).
- 1.2 %/a (2010 to 2050): assumed industrial economic growth until 2030 taken from (VCI and Prognos 2013), from 2030 to 2050 continued with growth rates from (BMWi 2010).
- 1.6 %/a (2010 to 2050): assumed industrial economic growth until 2030 taken from (VCI and Prognos 2013), from 2030 to 2050 linearly interpolated.

5. For paper production we chose a simplified method without stock modelling as paper is no homogenous good and one specific facility e.g. producing graphical paper can not be replaced by another facility with efficiency specifications according to the statistical average.

6. Real GVA for Germany was derived from German production statistics and deflated by values derived from macroeconomic accounting. NRW's real GVA was determined by the sales shares of NRW's enterprises.

Table 2. Numeric assumptions in the technology matrix. Source: own compilation, most assumptions approved by stakeholders, assumptions about lifetimes according to Fraunhofer ISI et al. (2011) and stakeholder information.

Sector	Process	technical life-time	Product	specific electricity consumption	net specific fuel consumption	availability date	Source
		a		GJ/t product	GJ/t product	year	
primary steel	BAT coke oven	40	t coke	0.1	40.1		IISI (1998), AllTech plant
	BAT sinter plant	50	t sinter	0.1	1.3		IISI (1998), AllTech plant
	BAT blast furnace (BF)	20 +20	t pig iron	0.3	12.5		own calculations
	DRI plant (H_2)	20	t DRI	1.3	12.1	2030	Sohn (2008); electricity: Nuber (2006)
	BAT basic oxygen furnace (BOF)	30	t steel	0.5	-0.8		IISI (1998), AllTech plant
	BAT electric arc furnace (EAF)	50	t steel	1.7	0.4		IISI (1998), AllTech plant; Worrel et al. (2008)
	smelt reduction and CCS	40	t steel	1.6	17.2	2025	Birat (2011)
aluminium	anode production	40	t anode	0.4	2.8		Worrel et al. (2008)
	BAT electrolysis	40	t aluminium	45	–		industry information
	advanced electrolysis	40	t aluminium	36	–	2030	own calculation based on Fraunhofer ISI et al. (2011)
	secondary aluminium	40	t aluminium	0.2	2.5		Worrel et al. (2008)
ethylene	BAT steam cracker with gas turbine	60	t ethylene	–	18		Ren et al. (2006)
	advanced steam cracker/ catalytic cracker	60	t ethylene	–	14.7 / 14.4	2020 / 2030	CEFIC (2013)
	advanced steam cracker/catalytic cracker & CCS	60	t ethylene	0.5	15.3	2030	CEFIC (2013)
cement	BAT cement kiln (6 cyclone stages)	40	t clinker	0.2	3.5		VdZ/ecra information
	cement kiln (6 cyclone stages) and CCS (post combustion)	40	t clinker	0.9	5.1	2030	VdZ/ecra information, Öko-Institut (2012)
	BAT cement grinding	20	t cement	0.1			VdZ/ecra information
	LC cement	20	t cement	0.2	1.7	2020 (pilot); large scale: 2035	Stemmermann et al. (2010), VdZ/ecra information
	LC cement grinding	20	t cement	0.3		2020 (pilot); large scale: 2035	VdZ/ecra information

For simplification and better comparison of technological pathways in this paper we focus on the – still optimistic – intermediate growth path which expects an average growth of NRWs industrial GVA of 1.2 %/a until 2050. This growth path is significantly above what industry has seen since 1990 and is also slightly higher than the 1.1 % per year increase in industrial value added as expected in the most recent 2013 Reference Scenario for the EU as a whole (European Commission 2013).

The industrial growth path of 1.2 %/a is linked to an expected increase in production of core basic industrial products until 2050 as assumed by the respective stakeholders[7] (see Table 4). The largest relative increase is foreseen for aluminium, while

7. Ethylene production was calculated by the model. The result was assessed as critical by stakeholders but accepted as a scenario.

Table 3. Electricity mix in Germany 2010–2050 and emission factors for electricity and heat. Source: own calculations based on AGEB (2012) and Destatis (2011) for 2010 values, WISEE.

net electricity production (TWh)	2010	2020	2030	2040	2050
lignite	129.2	130.6	100.4	77.9	27.1
coal	114.4	60.5	54.4	21.7	17.1
gas and oil	61.0	35.8	25.6	42.8	46.1
nuclear	133.5	54.5	0.0	0.0	0.0
renewables	88.2	240.4	354.4	435.0	494.4
total	534.9	532.8	544.7	587.2	593.4
Additionally: industrial CHP	47.7	46.7	52.1	53.1	47.7
emission factor electricity (kg CO_2/kWh)	0.53	0.40	0.31	0.21	0.12
emission factor CHP heat (kg CO_2/kWh)	0.22	0.25	0.25	0.25	0.25

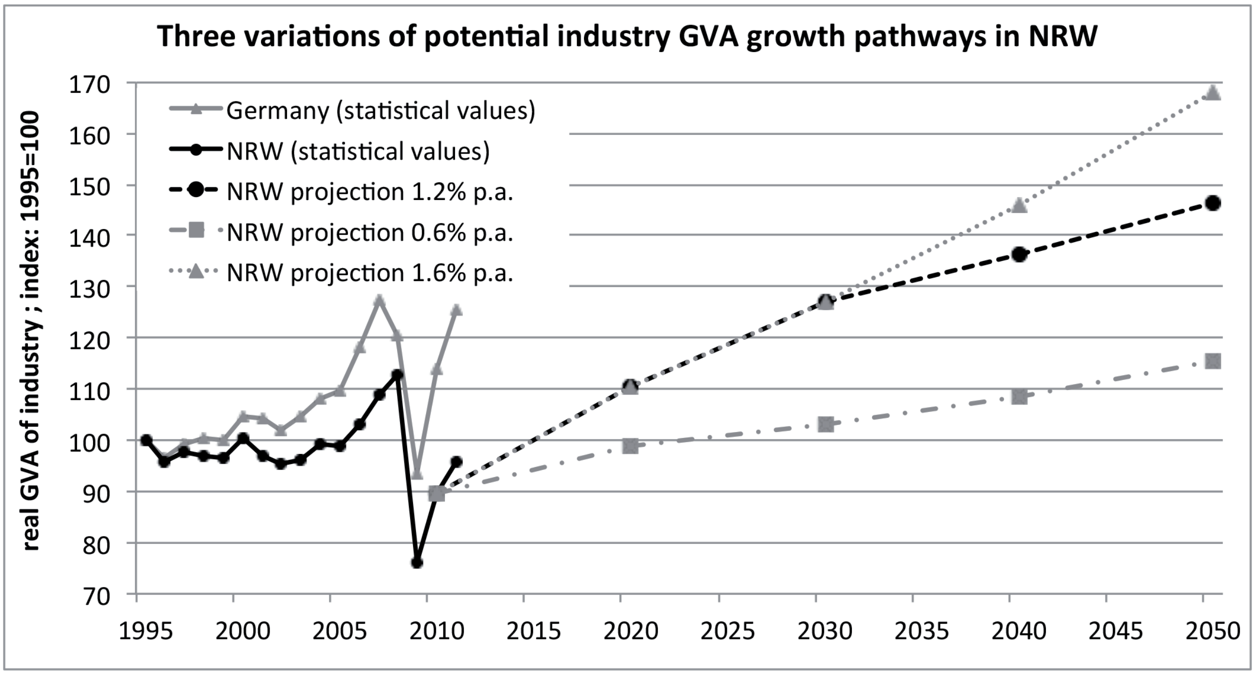

Figure 2. Three variations of potential growth pathways for industrial development in NRW. Statistical values based on Destatis and IT.NRW databases; projection based on VCI and Prognos (2013) and BMWi (2010).

in absolute terms increase of production of iron and steel is most substantial. Other productions taken into account here are expected to stagnate or even decline.

TECHNOLOGY PATHWAYS

Within the working group on industry as part of the climate protection plan process (see above), three technological pathways have been discussed intensely, especially with representatives from energy intensive industries. In this process one path relying on carbon capture and storage technologies was not seen as feasible by the stakeholders and thus did not become part of the developed scenarios within the process. Nevertheless this technology has been discussed and relevant parameters inhibiting this technology were identified. For this paper, this CCS path has been added to provide a broader range for comparison. Hence, the following three technology pathways have been modelled:

- The best available technology pathway (BAT) is based on best available technologies and an improved "operational excellence" in industrial production. Taking into account usual re-investment cycles, new facilities and equipment

Table 4. Overview on production volume development from 2010 to 2050 for the industrial GVA growth path of 1.2 %/a (Index 2010=1). Source: own calculation based on VCI and Prognos (2013) and industry information; ethylene production development based on model results.

production volumes	2010	2020	2030	2040	2050	change in %/a 2010–50
steel	1.00	1.08	1.16	1.24	1.33	0.71 %
aluminium	1.00	2.10	2.19	2.30	2.42	2.23 %
ethylene	1.00	1.14	1.10	1.01	0.71	-0.85 %
cement	1.00	1.00	1.00	1.00	1.00	–
paper	1.00	1.00	1.00	1.00	1.00	–

are purchased with best available technology and efficiency. This is true both for energy/emission intensive processes as well as efficient crosscutting technologies for all sectors as mentioned above. Additionally the share of industrial combined heat and power for heat provision is increased slightly, while simultaneously the electricity provided is increased due to higher efficiency of the CHP plants. In particular sectors (most prominently cement and paper production as well as CHP) a fuel shift from hard coal and lignite to natural gas or biomass is assumed. But this substitution does not offer a great potential throughout industry. Technological jumps or shifts in process structures are not taken into account. It is assumed that no new or breakthrough technology will come into play until 2050. This pathway and the underlying assumptions have been accepted by all stakeholders within the process, especially by those of each involved industrial sector.

- The low carbon technology pathway (LC) is based on the BAT scenario but goes beyond. A general assumption taken is that companies would accept a longer return of investment period (currently less than 1 year) and would be able to increase the upfront investments in order to tap the existing potentials in efficiency increase. With regards to technology the LC scenario assumes that improvements in energy efficiency beyond BAT become economic for crosscutting technologies. Further a slight shift to electricity-based technologies partly increases efficiency and reduces emissions thanks to a major decarbonisation of electricity supply. The major impact for mitigation though is linked to implementation of new breakthrough and low-carbon technologies for energy-intensive processes. The backbone of such a technological shift is the development of a hydrogen infrastructure for NRW, which is linked to excess renewable electricity. The electrolysers needed and respective hydrogen storage capacities would be situated in NRW close to the points of consumption. Electricity would mainly come via high voltage DC lines – already under construction – from North Germany, which in this scenario would supply huge amounts of excess electricity. Hydrogen will be used in the iron and steel industry as well as for various processes in chemical industry. Those technologies are currently commercially not available but exist in demo or pilot phase. The industry stakeholders within the working group approved most assumptions, although classified them as very ambitious.
- The carbon capture and storage pathway (CCS) keeps the assumptions taken for the LC path and adds the implementation of CO_2 capture and storage (CCS) in large industrial facilities. CCS so far has been discussed mainly as a mitigation option for power plants. In this scenario, CCS is also applied on large industrial sources, which partly provide a higher CO_2 content in the flue gas, but may impose other technical or economic challenges on the technology. The capture of CCS would be included in iron and steel making as well as in olefine production (steam crackers). Additionally, currently dispersed cement and lime production is assumed to be concentrated at one or two facilities so that CCS could be added to these emissions sources. In the discussions within the working group, the high costs and the lack of available storage facilities in the region as well as the perceived lack of acceptance have been major criticisms for regarding this pathway.

All three technology pathways BAT, LC and CCS are explained in more detail in Table 5. The differences of these pathways are linked to differing process technologies and their specific efficiencies. All pathways are based on new and up-to-date efficient crosscutting technologies for all sectors like electric motors, lighting or burning systems[8].

Results and Discussion

Scenario results for the selected production processes, i.e. primary steel, aluminium, ethylene, cement and paper production, are given in the following sub sections. At the end of the section we provide an overview on the results for NRW's industry as a whole and discussion.

Figure 3 gives an overview on energy demand reductions and Figure 4 on CO_2 mitigation. The total energy demand and CO_2 emission changes have been broken down for each sector

8. Please note that this analysis is based on technological potential and application and does not include economic aspects. The precondition for implementing these pathways are reliable economic and legislative framework conditions as well as public acceptance.

Table 5. Technology use in the scenarios BAT, LC and CCS. Source: compilation of Wuppertal Institute based on stakeholder discussions and literature cited in Table 2, approved by stakeholders.

Product	Technology		used in scenario		
			BAT	LC	CCS
cross-cutting	**CHP**	Integrated chemical/industry parks will continue to heavily rely on CHP supply. In paper industry CHP is extended also to smaller sites.	x	x	x
primary steel	**state-of-the-art BF/ BOF route**	All-Tech-Plant according to IISI (1998); blast furnace (BF) with high rate of coal infusion.	x	x	x
primary steel	**H_2-DRI**	Excess electricity used to produce high volumes of hydrogen for NRW's steel industry. Hydrogen used as reducing agent instead of coal in DRI process. Direct reduced iron is processed in an electric arc furnace. Produced steel may be used as an equivalent to products from the BF/BOF route (cold rolling is possible).		x	
primary steel	**BF and TGR**	Top Gas Recycling (TGR) as an option to retrofit existing BF from 2030 on.			x
primary steel	**smelt reduction & CCS**	In the CCS scenario no new installations in the BF/BOF route from 2030 on. New installations are then smelt reduction plants in combination with CCS (e.g. HISARNA).			x
aluminium	**state-of-the-art electrolysis**	From 2030 onwards, aluminium production may be concentrated at one site in NRW which will then be newly invested and use best available technologies.	x		
aluminium	**aluminium recycling**	Recycling of aluminium will increase due to higher scrap collection rates abroad.	x	x	(x)
aluminium	**advanced electrolysis**	From 2030 onwards, aluminium production concentrated at one site in NRW which will then be newly invested and use advanced technologies which omit process-related emissions reaching further efficiency.		x	(x)
ethylene	**State-of-the-art steam crackers**	Shrinking production volume; new investments are highly efficient steam crackers with improved heat integration and heat transfer using naphta as feedstock to a high extent. Olefine yields are maximised.	x		
ethylene	**advanced steam crackers/catalytic crackers**	Advanced steam crackers or catalytic crackers with additional efficiency potentials compared to state-of-the-art.		x	
ethylene	**advanced steam crackers & CCS**	Advanced crackers in combination with CCS.			x
cement	**slag use**	All available BF slags from steel production used to substitute clinker. Availability of BF slag depends on BF output which differs in the three scenarios.	x	x	x
cement	**state-of-the-art kilns with optimized use of biomass residues**	Share of biomass residues and waste rises until 2050 when it accounts for 80 % of the fuel share.	x		
cement	**Low Carbon cements**	So called Low Carbon cements can be produced with lower fuel use than clinker production. Also process-related emissions are lower. However, they can only be used as an additive in cement; the use of pure Low Carbon cements is assumed to be unrealistic from today's perspective. In 2050 they have an overall share of 14 %.		x	x
cement	**kilns with post-combustion CCS technology**	From 2020 onwards, cement production concentrated at some sites in NRW near the river Rhine, which will then be retrofitted with CCS technology from 2030 on.			x
paper	**efficient driers**	With no pulp production in NRW net electricity generation from paper production is no option for the domestic industry. In the BAT scenario highly efficient driers are used; CHP extended.	x		
paper	**lighter papers**	In LC scenario lighter paper sorts are introduced: standard office paper's weight is reduced from 80 to 70 g/m^2, newspapers' paper from 45 to 42 g/m^2.		x	(x)
paper	**electrification of driers**	In an energy system with high share of renewable electricity generation electrification of drying processes can further bring down emissions.		x	(x)

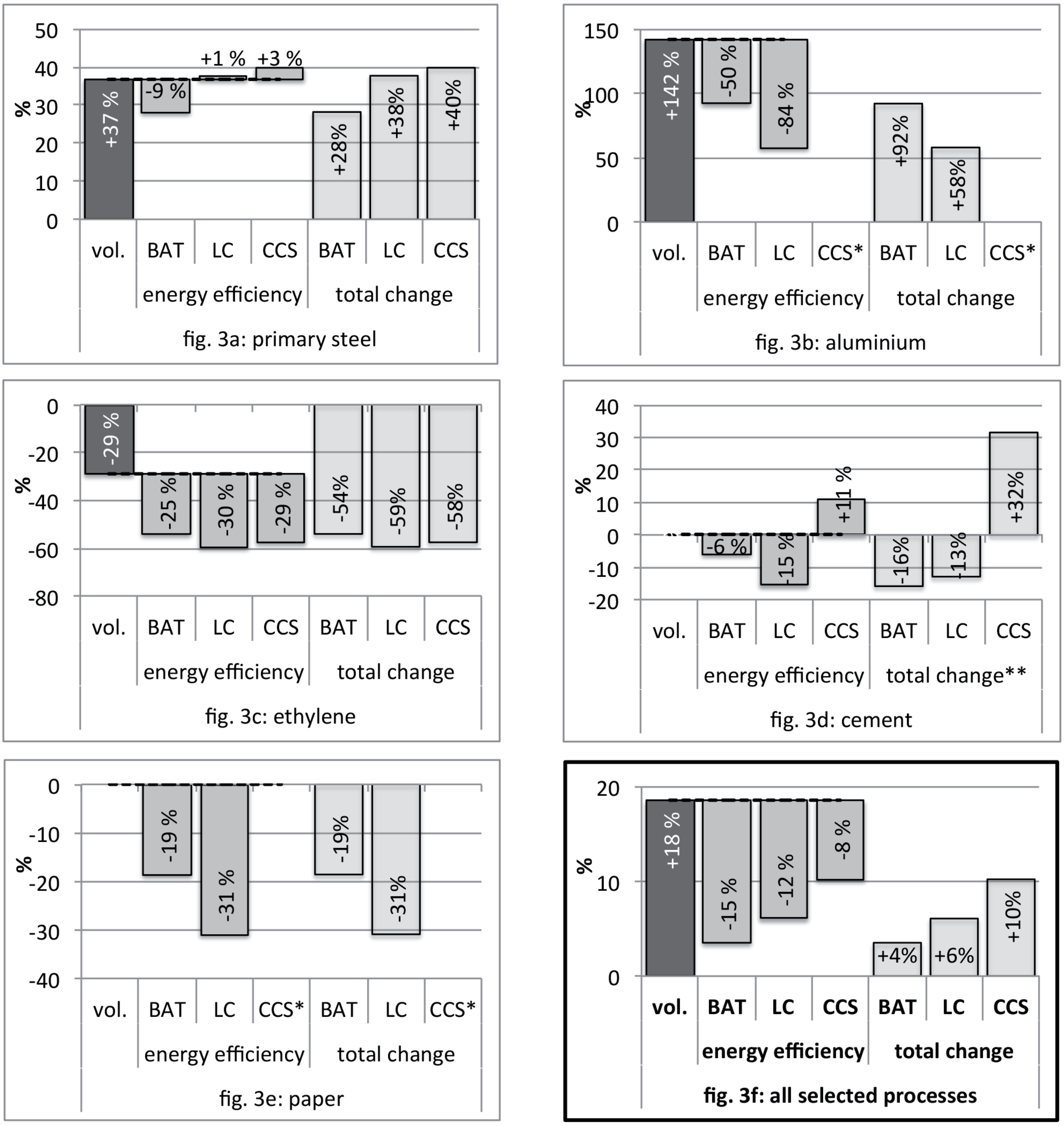

Figure 3. Energy demand change in selected industrial production processes; % change in 2050 compared to energy demand level in 2010. Source: own calculations.

* *CCS was not regarded in all sectors. In sectors with no CCS assumptions of the LC scenario were applied for the CCS scenario.*

** *Total change in cement industry also includes energy demand changes due to changes in the availability of blast furnace slag which were not subsumed in the categories "volume effect" or "energy efficiency".*

respectively to several single effects contributing to the total effect. The method is described in the following:

- "Volume effect" is calculated by up-scaling 2010's energy demand and emissions according to the production volume in 2050.
- "Efficiency effect" is calculated by rating 2050's production volume with the difference in specific energy consumption between 2050 and 2010 and the "effect of fuel switch" by rating with the difference in specific emissions (CO_2/GJ).
- The volume of captured and stored CO_2 determines the effect of "captured CO_2".
- The effect of "mitigation in the energy sector" is calculated by rating the demand of electricity and CHP heat with the difference in energy mix between 2050 and 2010 (emission factors of electricity and heat generation in CHP and public heat plants).

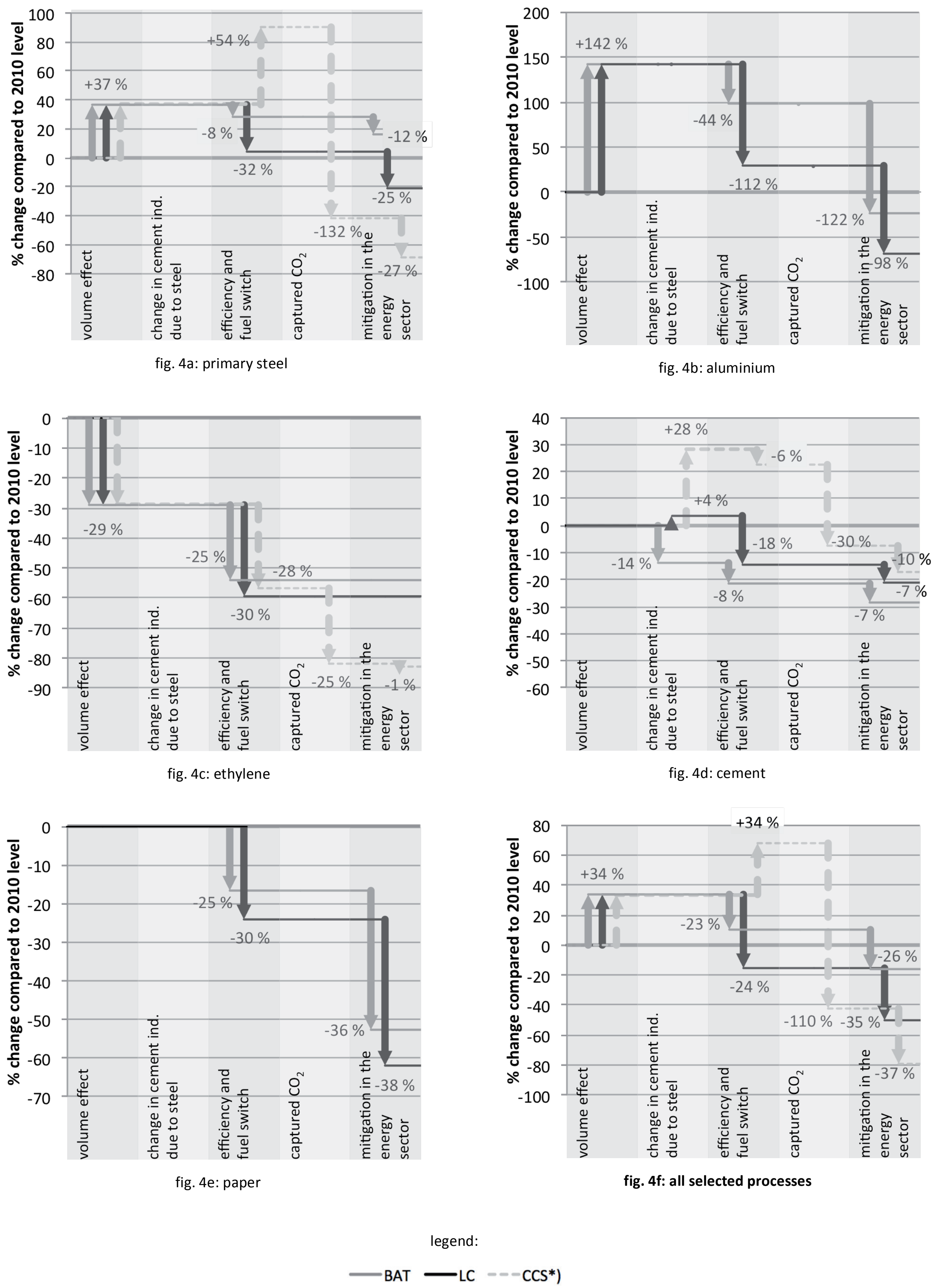

Figure 4. CO_2 mitigation in selected industrial production processes; % change in 2050 compared to emission level in 2010. Source: own calculations.

**In sectors with no CCS applied assumptions of the LC scenario were applied for the CCS scenario.*

PRIMARY STEEL PRODUCTION

We focus here on primary steel production, as primary and secondary steel are not homogenous goods.

Figure 3 shows that volume effect (+37 %) overcompensates efficiency effect in the BAT scenario as the saving potential of further energy efficiency measures is comparatively low in NRW's primary steel production with an existing production stock which is close to the state of the art. Total final energy demand increases by 28 % whereas CO_2 emissions rise by only 16 % as fuel switch (to a limited extent) and the restructuring of energy supply (reduced indirect emissions) contribute to CO_2 mitigation in addition to energy efficiency.

In the LC scenario direct reduction (DRI) with hydrogen and smelting in an EAF replaces the BF/BOF route to some extent, which is less energy efficient regarding final energy demand (+38 % final energy demand compared to 2010). But on the emission side efficiency losses are overcompensated by the switch from coal to hydrogen[9] as reducing agent.

In the CCS scenario energy demand also rises due to the additional energy demand of carbon capture. Nevertheless CO_2 mitigation is the highest in our scenario.

In both LC and CCS scenarios blast furnace slag is omitted by leaving the BF/BOF route leading – with cement production given – to a higher need of clinker production and higher CO_2 emissions respectively in the cement industry (see also below). If BF slag production is taken into account as a CO_2 credit, emissions allocated to steel industry in the base year are lower. The same is true for 2050, but the slag volumes are different: In the BAT scenario there is more BF slag than in the base year, in the other scenarios there is less slag. In the BAT scenario steel industry emits 16 % more CO_2 in 2050 compared to 2010 when disregarding slag, and 12 % more CO_2 if CO_2 credits for slag are taken into account. In the two other scenarios the higher level of GHG mitigation is diminished to some degree if we regard CO_2 credits for slag. In the LC scenario we calculated a CO_2 mitigation of 21 % (without credits) and of 20 % CO_2 with credits. In the CCS scenario the mitigation values are 69 % (without credits) vs. 61 % compared to 2010 respectively. The difference between the two values is the greatest in the CCS scenario where BF slag is completely omitted because of a total restructuring of the production stock (BF route is completely replaced by smelt reduction in 2050).

ALUMINIUM PRODUCTION

Aluminium production in NRW is characterized by a 50 % share of primary aluminium production in the base year 2010 with idle capacities however due to the economic crisis. It is assumed in all scenarios that primary aluminium production facilities will be operated at full capacity again in the years after 2010 and that the existing plants will be replaced in 2030 with an equivalent annual output. Secondary aluminium production increases during the whole scenario horizon until 2050, following the growth of the world market. In total aluminium production increases by 142 % compared to the base year 2010 (2.2 % p.a.). Specific final energy efficiency (50 % in BAT scenario) is achieved by the shift to secondary aluminium and the replacement of old facilities. In the LC scenario (CCS is not assumed for aluminium) primary aluminium production stock is assumed to become even more efficient (break-through technology, see above) resulting in a cut of 84 % of final energy compared to the production structure in 2010. In total final energy consumption of aluminium production in 2050 is 92 % higher in the BAT scenario than in 2010, in the LC scenario 58 %. If the 2050 final energy consumption level was provided by the 2010 energy mix in the energy sector, CO_2 emissions would rise by 98 % (BAT) and 29 % (LC) respectively, but the high share of electricity demand together with the restructuring process in the energy sector result in a total CO_2 mitigation of 23 % (BAT) and 68 % respectively (LC).

STEAM CRACKING FOR ETHYLENE PRODUCTION

Ethylene production is the interface between crude oil refining and chemical industry. Following the lower oil-based fuel demand in transport and households production is expected to shrink by 29 % (0.9 % p.a.) in our scenarios. Efficiency delivers an additional 25 % cut in energy demand and emission levels in the BAT scenario and 29 % in the LC scenario respectively. CCS will increase energy demand compared to the LC scenario by 4 % but bring down emission levels by 83 % compared to 2010. Respective mitigations in the other scenarios are 58 % (LC) and 54 % (BAT).

CEMENT PRODUCTION

Figure 4 reveals that CO_2 mitigation in cement industry is strongly dependent on the availability of by-products of steel production (blast furnace slag). Nevertheless, there are efficiency and fuel switch potentials in the clinker making process, which are interlinked. In our scenarios cement clinker production is characterized by a high share of renewable fuel surrogates as input into furnaces which limits the final energy efficiency potentials compared to the input of hard coal which is the benchmark regarding final energy efficiency. So energy demand reduction provided by efficiency measures is only 6 % in the BAT scenario. In the LC case – with a 14 % share of so-called LC cements (see above) – a 15 % cut is achieved. Overall energy demand is reduced by 16 % (BAT) and 13 % respectively (LC). In the CCS scenario – where blast furnace slag is no longer available – clinker production (with constant cement production) is by 11 % higher than in 2010. CCS requires additional fuel input and electricity, so total final energy input increases by 31 % compared to 2010. Total CO_2 mitigation is the highest in the BAT scenario and the lowest in the CCS scenario. So from this perspective assumptions for steel industry dominate the results in the cement industry. Whereas in the BAT scenario additional slag is a contribution to CO_2 mitigation in the cement industry of 14 % (ceteris paribus), lower slag volumes in the LC and CCS scenario result in a negative contribution to CO_2 mitigation (increase of CO_2 emissions by 4 % and 28 % due to the slag volume change). To show the actual achievements of cement industry, we made a second analysis. Segregating steel industry's impacts on cement production the results can be understood more easily: In the BAT scenario CO_2 mitigation compared to 2010 is 15 %, in the LC and CCS scenario 25 % and 45 % are reached.

9. Hydrogen's indirect emissions are rated with the factor zero here due to simplification. In our model runs we actually regarded hydrogen's effect on the electricity supply market. Emissions of electricity supply (incl. electricity needed for H_2 electrolysis) and heat supply are allocated to final electricity demand and final heat demand only.

PAPER PRODUCTION

Finally paper production shows an energy demand cut of 19 % in the BAT and 31 % in the LC scenario. In the LC scenario physical paper production is lower than in the BAT case (see above), this was rated as an efficiency effect, as the volume of useful products is the same in both scenarios.

CO_2 mitigation is considerably higher (BAT: 53 %; LC: 62 %) because of the high share of electricity demand in paper production, which is rated with the German electricity mix, which will be mainly based on renewable energies in 2050.[10]

AGGREGATED EFFECTS FROM SELECTED PROCESSES

The assumed development regarding the six core energy intensive production processes reveals some counterintuitive results:

- Total volume effects due to the relatively optimistic assumptions about future physical production of energy intensive goods lead to increasing energy use and CO_2 emissions in the portrayed production processes. Aggregated final energy demand will increase by 18 % and CO_2 emissions by as much as 34 % (due to an implicit switch towards coal, given high increases of steel production).
- This increase in final energy demand will only partly be compensated by improved technology in the BAT scenario, as final energy demand will increase by 4 % compared to 2010. In the LC scenario, however, final energy demand will increase even higher (6 % until 2050) as energy efficiency gains in aluminium, ethylene, cement and paper production are overcompensated by less energy efficient steel making which is however based to a considerable degree (40 %) on renewable hydrogen. The CCS scenario finally achieves lowest improvements in energy efficiency due to the high energy demand of CCS devices. Final energy demand increases by 10 %.
- With regards to overall CO_2 mitigation the situation is clearly the other way round. In the BAT scenario only 16 % reduction is achieved. Both the LC and the CCS scenario achieve higher CO_2 reductions; the LC scenario's 50 % reduction is due to an increased use of renewable energies via hydrogen and electricity and the CCS scenario reaches a 79 % reduction relying on fossil fuels and on the long term storage of captured CO_2.
- Total industry's energy demand in NRW (incl. all processes and cross-sectional technologies) rises by 7 % in all scenarios until 2020. After 2020 the energy demand in the BAT and LC scenarios decreases slightly to a 2050 level 3 % above 2010. In the CCS scenario, however, the additional energy demand of CCS results in stable consumption levels from 2020 on, so overall increase is still 7 % until 2050. Total industry's CO_2 reduction in the BAT scenario is 32 % in 2050 compared to 2010, 41 % in the LC scenario and 55 % in the CCS scenario. 90 % of the additional reductions – achieved in the LC and CCS scenario compared to BAT – can be attributed to the selected five products we examined in the paper at hand.

10. If electricity demand was rated with the fuel mix of industrial CHP in paper industry, emission reductions would be lower as – with very little domestic pulp production – biomass potentials are low in NRW's paper industry.

DISCUSSION

The scenario results can be understood and assessed more properly if our specific methodology of scenario building is taken into account as model philosophy and stakeholder participation play an important role. The technological bottom-up modelling approach applied here goes well with the participation of engineers with sectoral industry backgrounds representing one specific industry branch. It tends to underestimate long term efficiency potentials as it is based on today's knowledge about technologies (cp. Nielsen & Karlsson 2007, 312). Industry stakeholder participation leads to conservative assessment of existing efficiency potentials and to rather optimistic assumptions on the performance of the own industry branch, whereas NGOs stressed in the process that further efficiency and GHG mitigation gains could be realised by new technologies that are far from economically viable today. This discussion was reflected with several scenarios on industry development.

It is interesting to compare industry's contributions to GHG mitigation with the contributions of other sectors which were investigated in parallel in similar processes of modelling and stakeholder participation. Final energy demand of industry goes down by only 0.1 % per annum in industry in the BAT scenario (even slightly increases in the LC and CCS scenarios) whereas in the household sector – with a strong refurbishment strategy – 2.9 % final energy savings are achieved per annum; service sector achieves 1.0 % and the transport sector 1.2 %. As mentioned above we examined further scenarios of industry with differing assumptions on growth of industry gross value added (GVA). In a scenario combining lower industry growth (0.6 % p.a.) with LC technologies final energy demand decreases by 0.5 % p.a. and in the respective LC scenario with a stronger GVA growth rate of 1.6 % there is an annual increase in final energy demand of 0.3 %. Nevertheless, in all of our scenarios final energy demand reduction in industry is lower than in the other sectors.

This leads to significant increase of industry's share in NRW's GHG emissions. Industry's direct emissions will by 2050 reach a share of more than 30 % in the LC scenario compared to 18 % in 2010 (without industrial CHP). This could have several consequences: Either, other sectors would have to compensate for the slow emission reductions in industry which means the legal target of reducing NRW's GHG emissions by 80 % vs. 1990 could only be achieved if electricity generation is almost fully converted to renewable energy sources by 2050. Another consequence could be the that the state NRW would increase its share in emissions under the European Emission Trading System from 11 % in 2010 to 30 to 60 % by 2050, if GHG emission ceilings according to the reduction range given in the Low Carbon Economy Roadmap (European Commission 2011) would be enacted. Such a development would mean that the industry would have to import a significant amount of emission rights from other regions and have to cover the cost of it.

Conclusion

Due to the specific participatory design of a climate protection plan for the German state of North Rhine-Westphalia and with the purpose to improve on important shortcomings of conventional scenario analyses (cp. Nielsen & Karlsson 2007) our stakeholder-based analysis of future developments of industrial energy use and GHG emissions generated some important results with regards also to national and European energy and climate policy.

- It shows that a policy of "re-industrialization" or even bringing basic industries back on a slow growth path would come with significant pressure on energy demand.
- The analysis of BAT and further technology options makes it clear that this trend cannot be fully compensated by more efficient technology, partly because in very energy intensive productions possible improvements become increasingly incremental.
- In order to significantly reduce greenhouse gas emissions from heavy industry – which is still an important emitter – the development and implementation of new breakthrough technologies such as electrification, hydrogen based processes, alternative cements or CCS becomes necessary.
- Those technologies, however, often are no longer linked to improved energy efficiency but are often using more energy than conventional BAT, a fact that is most pronounced for CCS. Thus low carbon technologies for heavy industry have to rely on the supply of sustainable renewable energy via electricity or hydrogen, or on the long-term storage of CO_2. However, the negative effect on efficiency showed in our analysis may be exaggerated, as the LC technologies are not well explored yet in contrary to "conventional" processes.

We therefore can conclude that decarbonising basic industries is a huge challenge, which is becoming increasingly important, as industry's share of total greenhouse gases – contrary to the past where industry due to technology improvement but also to structural change always showed high rates of decline – might increase again in the future. This trend could become quite significant as efficiency improvements are increasingly exploited and remaining potentials decline and policy is trying to maintain a certain share of domestic production also of basic industrial goods. The fact that growth rates assumed here for energy intensive basic products are well below expected global growth rates leads to the question how much physical goods and products can be produced globally given energy, climate and resource constraints and if limitation of physical growth has to be taken into account as a policy strategy for the European Union.

In spite of these challenges, an active decarbonisation strategy can also be a chance for energy intensive industries to maintain their already pronounced profile of high tech and high value added producers as compared to global production. It would also be a strategy to put industry and technology providers into a pole position in the global arena.

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