A transition pathway for Germany's industry: which role for energy efficiency?

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Abstract
Germany's Government has committed to an energy transition that reduces greenhouse gases by at least by 80 % by 2050 compared to 1990 level. This goal requires ambitious action in all sectors, also the industry, which emitted about 21 % of Germany's total GHG emissions in 2013.

We present a mitigation scenario that achieves a reduction in GHG emissions of 83 % by 2050 for the industrial sector. While this paper presents results for the industry sector, the scenario calculations have been accompanied by similar scenarios in all sectors aiming to achieve a total GHG mitigation of 80 % for the entire economy. The industry scenarios are based on the bottom-up model FORECAST, which allows simulating policies and induced technical change. It provides a very detailed breakdown of technologies.

The resulting transition pathway reveals high importance of energy efficiency, particularly in electric motor systems, innovative process technologies and steam systems. It is resulting in a reduction of electricity demand by about 16 % and a reduction of fuel demand by about 32 % from 2010 to 2050. This shows that energy-efficiency alone is not sufficient – although important. The use of biomass increases to about 120 TWh in 2050. Coal is phased out in all sectors but in the iron and steel industry, which also experiences a drastic shift towards electric steel. Secondary production routes and alternative materials are also increasingly employed in paper, cement, glass and aluminium industries. By 2050, carbon capture and storage mitigates about 24 Mt CO_2 annually from emission-intensive processes (clinker and lime burning, steel, ammonia, ethylene and methanol). Power-to-heat gains importance after 2040 and reaches about 29 TWh in 2050. This scenario reflects a radical change to be achieved in less than 35 years, while the industry sector often shows high reluctance towards new policies and has a very long-living capital stock.

Introduction
In 2013 the industrial sector consumed 710 TWh of final energy, which equalled to about 28 % of Germany's total final energy demand (BMWi 2016). Energy related greenhouse gas (GHG) emissions were amounting to 125 Mt of CO_2. Process related emissions (not based on energy conversion) from individual industrial processes add 45 Mt of CO_2-eq resulting in total industrial emissions of about 170 Mt CO_2-eq in 2013 (BMWi 2016). This equals to 21 % of Germany's total GHG emissions making the industrial sector a major emitter. The share would have been higher when also accounting for embedded emissions in electricity and district heating consumed. The industrial sector consumed 44 % of electricity demand (final energy) and 43 % of district heating demand in Germany in 2013. Since 2000 both final energy consumption and energy-related GHG emissions remained on a constant level indicating that no substantial fuel switch towards low-carbon fuels has taken place. Process-related emissions slowly decreased since 2000.

In 2010 the German government adopted the so-called "energy concept" setting long-term targets for GHG mitigation and related sub-targets for individual sectors (Bundesregierung 2010). Accordingly, Germany aims to reduce its GHG emissions by 2050 by at least 80 % compared to 1990. Such a reduction requires a complete transition in the energy system including electricity generation and consumptions as well as fuel use for transportation and industrial processes. This transition has been labelled the "Energiewende" in Germany. The most recent monitoring report for the "Energiewende" (BMWi 2015) reports an achieved GHG reduction of 27 % in 2014 compared to 1990.

A transition like the "Energiewende" requires numerous policy interventions and adjustments of the legislative framework of the energy sector. Challenges for policy makers are multiple. Different transition paths may lead to different outcomes in terms of costs or environmental impact. Future developments need to be anticipated to steer such an inertial process and react in time. E.g. certain new technologies might be required to achieve a specific level of GHG reduction, but they might not yet be available on the market. Energy scenario analyses can support this process by providing information on transition paths related to technologies required, costs and environmental impact.

We aim to assess a transition path for the industrial sector in Germany using a bottom-up simulation model. We use the model FORECAST-Industry, which is a technology-rich bottom-up model. It aims to simulate investment decisions related to "real-life" decisions by investors. E.g. the adoption of energy-efficiency measures (EEMs) is based on their payback time as observed in empirical studies. Also other barriers to the adoption of EEMs are considered. This allows a detailed modelling of policy instruments such as minimum energy performance standards (MEPS), prices or taxes. To summarize, our methodology does not allow drawing conclusions on a least cost path, instead it allows insights into policy instruments needed. Costs are considered from a private investor perspective.

Many comparable analyses use an approach that calculates a reduction path based on minimized total system costs. For example Fais et al. (2016) use the TIMES model and follow an optimization approach to calculate mitigation scenarios for UK's industry. They consider the entire energy system and set targets for CO_2 abatement. Some energy-intensive processes are modelled in a very detailed manner while others are more aggregated as end-uses.

Our work presented here is part of a broader assessment based on detailed bottom-up calculations for the entire energy sector including buildings, transport and central heat and electricity generation. Such a broad perspective is important, because strong interdependencies to other sectors exist. These are e.g. related to the allocation of resources like biomass, the level of ambition, infrastructure and demand-supply interaction.

The overall objective of at least 80 % reduction in GHG emissions also includes emissions in non-energy sectors such as agriculture. Because these are particularly difficult to mitigate[1], the energy sector has to overachieve its target. Consequently, we assume that also the industrial sector has to achieve at least 80 % GHG reduction by 2050.

With regard to the availability of biomass we assume that only sustainable domestic biomass sources can be used making biomass a scarce resource. While much of it is required in the transport sector, also for high temperature industrial processes biomass use can be further increased compared to today's use.

The industrial sector also has links to the power market, particularly, when related to the use of combined heat and power as well as the use of intermittent wind and solar energy for heat generation. This link is captured in the model system by including the process heat demand (<500 °C) in the power market optimization model.

In the following, we first present the methodology focussing on the bottom-up model FORECAST before we present scenario definitions and assumptions. Finally, results are shown and discussed, particularly focussing on the role of energy efficiency.

Methodology – the model used

The methodology relies on scenario analysis based on bottom-up modelling. The scenario calculations are conducted using the bottom-up energy demand model FORECAST-Industry. In the following a brief description of the model is provided. For additional information, we refer to the model website[2] and a number of publications as mentioned below.

Compared to the other sectors, the industrial sector shows the highest degree of heterogeneity with regard to technologies and energy users (i.e. companies). This poses a huge challenge to a bottom-up model, which mainly focuses on large homogenous groups of energy uses/ energy services. At the same time, the number of energy uses should not be too high, as gathering input data is very time and resource intensive.

Thus, the structure of the industrial sector module also reflects this heterogeneity and the data availability in the industrial sector. Selected energy-intensive processes are explicitly considered, while other technologies and energy-using equipments are considered in the form of cross-cutting technologies modelled similarly across all sub-sectors. The model is a simulation model, which reflects the fact that the investment decisions are modelled according to real-life behaviour of investors. Thus, in contrast to often used optimization models FORECAST does not calculate the energy system based on least system cost. Instead, barriers to the adoption of energy efficient technologies are considered. Considering barriers and sub-optimal behaviour of investors also allows including various policy instruments such as standards, taxes and subsidies.

Following data availability and heterogeneity also different approaches are used in the various modules to simulate technology diffusion. These range from diffusion curves to vintage stock models and discrete choice simulation.

Figure 1 shows the simplified structure of FORECAST-Industry. It comprises the following main sub-modules:

1. **Energy-intensive processes**: this module presents the core of the bottom-up quantity structure of FORECAST. 64 individual processes/products are considered via their (physical) production output and specific energy consumption (SEC). The diffusion of about 200 individual energy efficiency measures (EEMs) is modelled based on their payback period (Fleiter et al. 2013; Fleiter et al. 2012).

1. E.g. emissions from agriculture are bound to biological processes and can only partly be mitigated based on available technologies. Ambitious mitigation requires fundamental behavioural change in terms of a changing diet (Öko-Institut, Fraunhofer ISI 2015).

2. http://www.forecast-model.eu

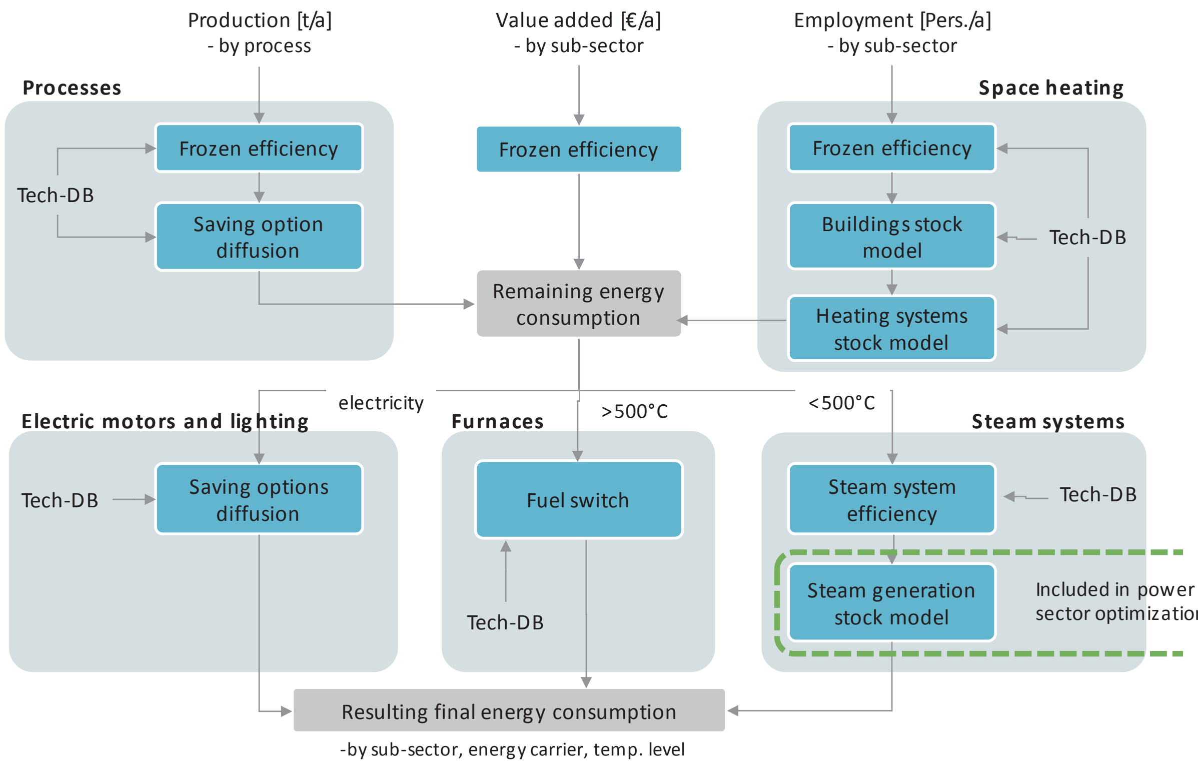

Figure 1. Overview of the model FORECAST-Industry.

2. **Space heating**: space heating accounts for about 9 % of final energy demand in the German industry. We use a vintage stock model for buildings and space heating technologies. The model distinguishes between offices and production facilities for individual sub-sectors. It considers construction, refurbishment and demolition of buildings as well as construction and dismantling of space heating technologies. The investment in space heating technologies such as natural gas boilers or heat pumps is determined based on a discrete choice approach (Biere et al. 2014).
3. **Electric motor systems and lighting**: these cross-cutting technologies (CCTs) include pumps, ventilation systems, compressed air, mechanical equipment, cold appliances, other motor appliances and lighting. The module captures the individual units as well as the entire motor-driven system including losses in transmission between conversion units. The electricity demand of the individual CCTs is estimated based on typical shares by sub-sector. The diffusion of EEMs is modelled similarly to the approach used for process specific EEMs.
4. **Furnaces**: energy demand in furnaces is a result of the bottom-up estimations from the module "energy-intensive processes". Furnaces are found across most industrial sub-sectors and are very specific to the production process. Typically they require heat on a very high temperature level. While EEMs for individual furnaces are modelled in the module "energy-intensive processes" the module on furnaces simulates price-based substitution between energy carriers. The method is based on a random utility model (logit model). The model is calibrated using revealed preferences data gained from regression analysis of historic time series – a similar method is used by Kesicki, Yanagisawa (2015).
5. **Steam systems**: the remaining process heat (<500 °C) is used in steam systems throughout most sub-sectors. The module comprises both the distribution of steam and hot water as well as its generation. As very little information is available about the performance of existing steam distribution systems, we assume exogenous efficiency improvements for each scenario based on available literature. Steam generation is included in the optimization of central heat and power generation to allow for capturing the interdependencies between the two sectors. This link allows considering the benefits of electricity from CHP generation and power-to-heat as a way to use electricity in times of high wind and solar generation.

All modules described above consider 14 individual sub-sectors using the definition of the German energy balances. The model FORECAST is based on a hierarchical structure as shown in Figure 2. 64 energy-intensive processes are considered and each is allocated to one sub-sector. CCTs are also considered by sub-sector as share of electricity demand of the respective sub-sector. The energy demand of CCTs and processes can overlap. E.g. the electricity demand of a paper machine mainly comes from electric motors to provide mechanical energy. This is accounted for in the process "paper" as well as in the individual CCTs like pumps, machine tools and other electric motors. Both do present a different perspective on the same demand. EEMs are considered for processes as well as CCTs. The former include EEMs related

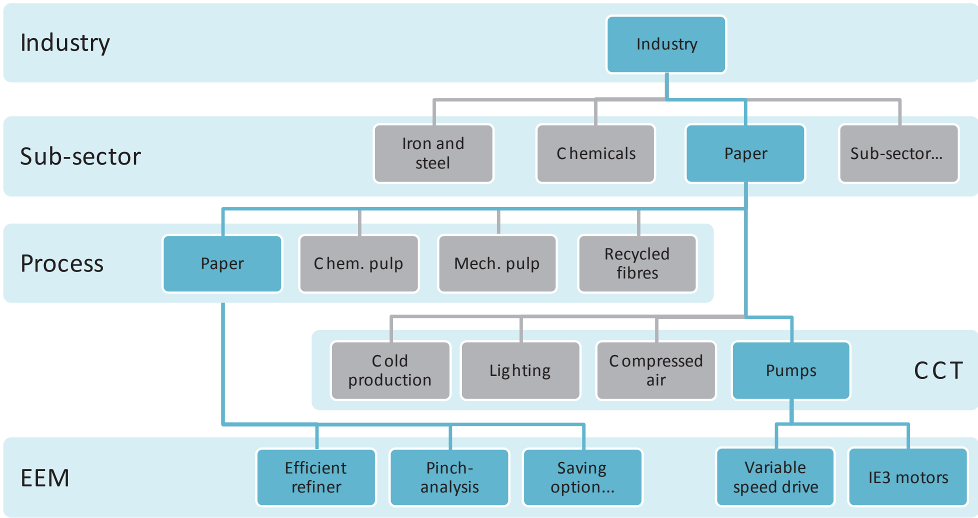

Figure 2. Hierarchical structure of the FORECAST-Industry model for process technologies and cross-cutting technologies (CCTs).

to the process characteristics and the latter EEMs that are of a horizontal nature like replacing electric motors. Energy demand of processes and CCTs changes when EEMs diffuse through the technology stock.

Scenario definition and input data

We define two scenarios: A reference (REF) and a transition (TRANS) scenario.

- The **REF scenario** describes a world without energy transition. Past trends continue and implemented policy instruments like minimum energy performance standards also remain alive. Subsidies are phased out after 2020.
- The **TRANS scenario** aims at a reduction of Germany's GHG emissions by at least 80 % by 2050 compared to the level in 1990.While not all sectors are required to contribute equally[3] to this reduction, we assume that the industry sector has to arrive at a minimum of -80 % by 2050.

Both scenarios are mainly distinguished in the intensity of individual policy instruments. Some policies can be individually modelled while others are rather represented in terms of investor behaviour or technology trends and the specific policy design remains open.

The model requires input data on the performance of technologies, macro-economic frameworks, prices as well as policy-related assumptions. The most important input parameters are summarized in the following. If no particular indication for scenarios is given, the assumptions are the same in both scenarios.

Economic framework parameters and **energy prices** are the same across scenarios to allow a maximum comparability. The specific input parameters are summarized in Table 1. The assumptions reflect a continuation of economic growth in industry and structural change towards a less energy-intensive industry. The prices of all energy commodities are increasing. No major new break though technologies or fundamental structural changes are continued. Historic trends are assumed to continue in the future.

Technology assumptions are the same in both scenarios with regard to the performance of energy supply technologies. Also technological learning takes place at the same pace. We do, however, assume that the TRANS scenario experiences an earlier availability of innovative production technologies in energy-intensive industries; e.g. low-carbon cement production. CCS is assumed to be available in the TRANS scenario from 2030 onwards while it is not considered in the REF scenario. Material efficiency improvements and trends to **secondary production** are more pronounced in the TRANS scenario whereas they reflect historical trends in the REF scenario. Secondary production routes comprise production based on recycled materials (e.g. recycled paper, electric steel or secondary aluminium). The increase in secondary products is only based on domestically available resources. Imports are assumed to remain on a similar level as today. E.g. the shift from oxygen steel to electric steel production is taking place faster in the TRANS scenario and represents an ambitious path alongside the maximum scrap availability (Herbst et al. 2014).The scrap availability was estimated based on Germany's steel infrastructure and typical reconstruction cycles. See Table 2 for an overview of major shifts to secondary production.

Material efficiency that results in a reduced demand (and thus production) of energy-intensive products has been considered as exogenous input on a product specific basis. The TRANS scenario assumes increased material efficiency compared to the REF scenario. Until 2050, the improvements result in a reduction of the annual production output in the range of 3–5 %. These assumptions are included for steel, aluminium, zinc, paper, glass, cement, ammonia, chlorine, ethylene, methanol, plastics and meat. Despite the lack of empirical studies, we think that the available potentials are higher than what is assumed here. The challenge certainly is the implementation of effective policies and strategies to exploit the existing potentials. Allwood et al. (2011) provide an overview of the various options available.

3. Ideally, the contribution of each sector should be based on marginal costs. However, in practice, they are often difficult to estimate for very ambitious long-term scenarios. Still, the individual sector contribution is following cross-sector comparison of ambition levels roughly reflecting also marginal costs.

Table 1. Summary of main macro-economic framework and price assumptions (Assumptions are similar for both scenarios if not otherwise indicated).

Input parameter	Specification
Value added [$Euro_{2010}$/a]	Industry total: 0.7 %/a Machinery and transport equipment: >1 %/a Energy-intensive industries: <0.5 %/a
Employment [persons/a]	Total employment falls from 7.4 million in 2010 to 4.5 million in 2050 Strong decrease in energy-intensive industries
Production [t/a]	Continuous slow increase for most products The TRANS scenario experiences stronger structural change towards secondary production and faster material efficiency progress (see Table 2)
Energy prices [$Eurocent_{2010}$/ kWh]	Prices of fossil energy carriers increase by 63 to 77 % from 2010 to 2050 Electricity price increases by 28 % from 2010 to 2050 District heating price increases by 118 % from 2010 to 2050

Table 2. Summary of main assumptions with regard to secondary production and circular economy (it is assumed that only domestic resources are used; import and trade is kept constant).

Parameter	2000	2010	2030		2050	
			REF	TRANS	REF	TRANS
Steel: share of electric steel	29 %	30 %	39 %	47 %	42 %	57 %
Aluminium: share of secondary aluminium	47 %	60 %	65 %	68 %	73 %	77 %
Copper: share of secondary copper		43 %	43 %	46 %	43 %	49 %
Paper: share of recycled fibres	86 %	85 %	89 %	90 %	92 %	95 %
Cement: clinker share	74 %	77 %	70 %	63 %	67 %	54 %

Besides the above mentioned technical and economic assumptions, the model FORECAST also allows for the analysis of detailed **policy assumptions**. Particularly standards (MEPS), prices and taxes can be considered in detail. Other policies like energy audits and energy management systems that address information and knowledge gaps are modelled more generically. The REF scenario represents a world without energy transition. Currently implemented regulative instruments remain as they are but will not be revised. Subsidy programs will be phased out in 2020 and price based policies, mainly the EU emissions trading scheme (ETS), will continue with low ambition (i.e. a low price path). The TRANS scenario includes policies that can contribute towards the objective of at least 80 % GHG mitigation in the industrial sector. These policies include more ambitious regulative instruments like product standards, subsidies for innovative technologies, instruments that enable electric motor system optimization, high EU ETS price path that reaches 100 Euros/tonne in 2050 and company's anticipating the price 5 years ahead, a CO_2 tax on a similar level for the non-ETS sector, more ambitious material efficiency and circular economy activities as well as successful R&I for energy-intensive processes (see Table 3 for a complete overview).

For process technologies and cross-cutting technologies (CCT) energy efficiency improvement is modelled via the **diffusion of energy efficiency measures (EEMs)**. The diffusion is modelled following a two-step approach: First, diffusion boundaries are defined and, second, the diffusion path is calculated based on the payback time of EEMs:

1. As EEMs can describe very different technologies or behavioural changes that improve energy efficiency (i.e. reduce the specific energy consumption of a process or a CCT), diffusion dynamics can vary substantially among the individual EEMs. E.g. some might need replacement of existing capital stock, while others are add-on technologies and might diffuse faster. To cope with this heterogeneity, exogenous diffusion boundaries are defined for each EEM individually in the form of a maximum and a minimum diffusion curve. They follow the form of logistic curves. For the maximum diffusion we assume that no premature replacement of existing capital stock can take place. The minimum diffusion can in some cases be very low or even zero. Minimum energy performance standards (MEPS) in the framework of the EU Ecodesign Directive are included in the model by lifting the minimum diffusion to a level that represents a forced high market share of EEMs. In this case, the minimum diffusion may even follow the same path as the maximum diffusion.

2. The resulting diffusion of an EEM lies between these two boundaries. The diffusion speed is determined by the payback period of the EEMs. For example a longer payback period results in slower diffusion and thus a diffusion curve that is closer to the minimum path. The diffusion speed can thus be regarded as the share of companies implementing a certain EEM where the maximum diffusion represents 100 % of technically feasible implementation. In order to consider heterogeneity across companies the investment decision is not modelled as a discrete threshold but as a continuous function based on a logistic growth model. This

Table 3. Overview of policy assumptions by scenario.

Type of instrument	Instrument	REF scenario	TRANS scenario
Regulative instruments	Minimum energy performance standards (MEPS) (EU-Ecodesign Directive)	Standards remain, but will not be revised. Regulations already decided will still be implemented.	Continuous revision following least lifecycle cost.
	Building standards (Energy saving ordinance)	Remains on current level.	Little more ambitious than in REF.
	Exceptions from electricity price surcharge (so called “Spitzenausgleich” and “EEG-levy”) coupled to requirements for the implementation of energy management systems	Remains as is. *The model implementation is done in an aggregated way via changed assumptions on investment decision thresholds (see Figure 3).*	Ambitious implementation of energy management systems. *The model implementation is done in an aggregated way via changed assumptions on investment decision thresholds (see Figure 3).*
Subsidies	Financial support of high efficiency cross-cutting technologies	Phase out of financial support.	Increase in total financial support and particular (successful) focus on system optimization.
	Financial support of energy audits for SMEs	Phase out of financial support. The model implementation is done in an aggregated way via changed assumptions on investment decision thresholds (see Figure 3).	Increasing support and number of audits The model implementation is done in an aggregated way via changed assumptions on investment decision thresholds (see Figure 3).
Instruments based on prices and quantities	Emissions trading (EU ETS)	EU ETS remains as designed in the 3rd trading period. Price is exogenously assumed and increases to 30 Euros/t CO_2 in 2050. Companies do not anticipate increasing prices.	EU ETS remains as designed in the 3rd trading period. Price is exogenously assumed and increases to 100 Euros/t CO_2 in 2050. Companies anticipate increasing prices five years ahead, thus assuming a stringent and well communicated commitment to the EU ETS.
	CO_2 tax	No particular CO_2 tax. Only existing energy taxation.	A CO_2 tax is implemented for the non-ETS sector to incentivize fuel switch to low-carbon fuels. The tax equals the ETS CO_2 price. Companies anticipate increasing prices five years ahead.
Strategies	Material efficiency and circular economy	Slow increase in recycling rates based on historic trends.	Increase in material efficiency and recycling rates assumed.
	Efficiency via systems optimization	–	Remaining potentials are nearly completely exploited.
	R&D and innovation	–	Successful market introduction of innovative process technologies in energy-intensive industries (e.g. low-carbon cement).

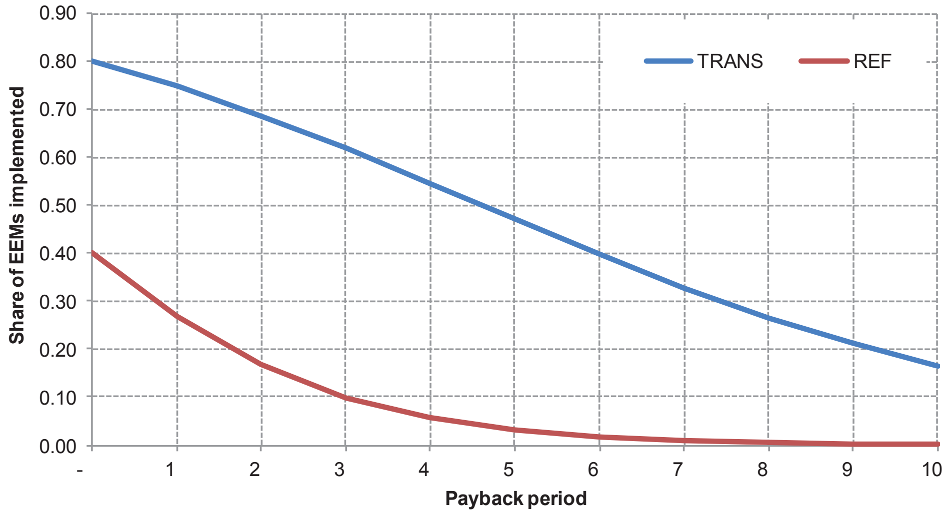

Figure 3. Payback period thresholds by scenario.

approach assures that even with a longer payback period a few companies are investing, and the adoption rate is continuously increasing with decreasing payback period. Figure 3 illustrates the relation between payback period and implementation rate for individual EEMs. E.g. in the REF scenario 10 % of the companies would implement EEMs with a payback period of 3 years, whereas in the TRANS scenario the implementation rate would be about 60 % with the same payback time.

Carbon capture and storage (CCS) is considered as mitigation option in the TRANS scenario. We assume that from 2030 it enters the market, which implies that by 2030 the required legislative regime is defined and that the technology is available. The market diffusion of CCS is modeled based on its profitability. The technologies' profitability depends on various costs (investment, running cost, energy demand) as well as the CO_2-price savings. We assume continous reduction in investment costs due to technology learning. Current and future technoloy costs and other characteristics are based on the comprehensive review by Kuramochi et al. (2012).

We consider CCS for selected industrial point sources. These were identified in a first step based on the amount, the intensity and the purity of emissions. This led to the following processes for which we allow CCS in the model: integrated steel production (blast furnace), burning of clinker and lime, methanol production, ethylene production (steam cracker) and ammonia synthesis. Issues related to acceptance among the population and distance to storage locations are not explicitly considered. In the reference scenario, CCS is not considered.

Results

GHG emissions are continuously decreasing in both scenarios from 2010 until 2050 as shown in Figure 4.

Process related emissions account to 29 Mt CO_2 in 2010 and decrease to 22 Mt in the TRANS scenario and 26 Mt in the REF scenario by 2050. In the TRANS scenario, 11 Mt of this are stored via CCS (part of CCS bar in Figure 4). The slow reduction of process-related emissions is explained by the fact that they are related to the production of clinker, lime, ammonia and methanol, which also does not change substantially. Only for clinker, the TRANS scenario assumes a minor reduction of emissions per ton of production due to new low-carbon cements.

Energy-related emissions experience a more substantial reduction even without CCS in both scenarios driven by both a reduction in total final energy demand for fuels and a switch towards less CO_2 intensive fuels. In the REF scenario energy-related emissions decrease from 111 Mt CO_2 in 2010 to 81 Mt in 2050, while the TRANS scenario shows a reduction to 49 Mt, of which CCS captures additional 24 Mt.[4]

In total, 35 Mt CO_2 emissions are remaining in the TRANS scenario in 2050 (energy-related and process-related). This reflects a reduction of 83 % compared to the 215 Mt CO_2 in 1990.

Note that the 215 Mt CO_2 only include process-related emissions from clinker, lime, ammonia and methanol. Additional minor sources of process emissions as well as N_2O and other greenhouse gases from industrial sources are not included. Many of these (particularly N_2O in adipic and nitric acid production) have very high abatement potentials and already reduced substantially in the past (DEHSt 2014). The emissions balance in 2010 differs from the emissions mentioned in the introduction because we do account process related emissions from the steel industry differently. Also, as mentioned above, not all process-related emission sources are accounted for.

Final energy demand (FED) is also decreasing in both scenarios until 2050, however, a lot slower than GHG emissions. Figure 5 shows the resulting energy demand by energy carrier and scenarios in comparison. The REF scenario shows a continuous reduction of FED that has also been observed in the past two decades. In total, final energy demand decreases by 13 % from 2010 to 2050. Also the shares of energy carriers change,

4. In total (process and energy-related emissions) 35 Mt CO_2 are captured and stored in 2050. The annual storage cumulates to 463 Mt CO_2 until 2050. For comparison, the total storage capacity in Germany is estimated to about 15–31 Gt CO_2 Grünwald 2007.

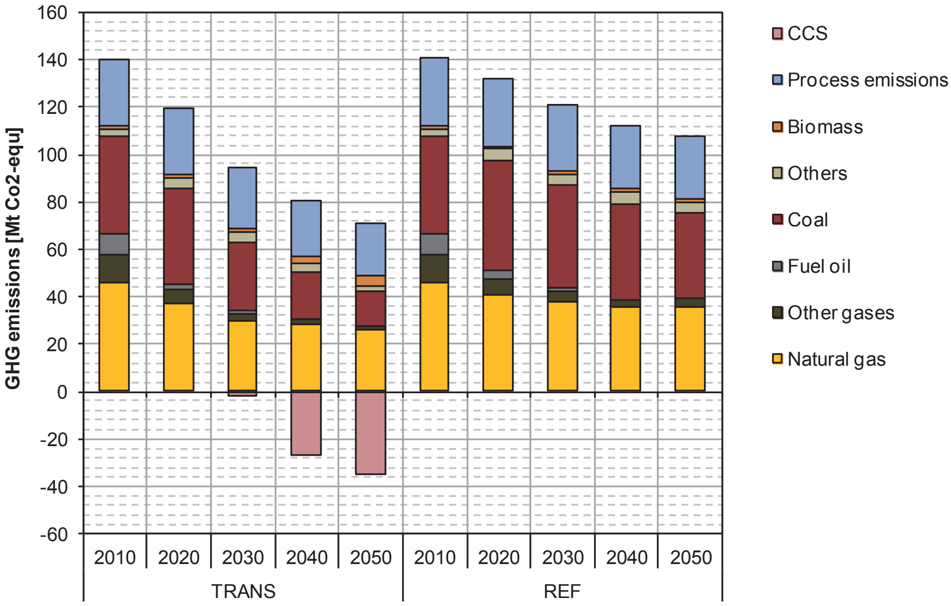

Figure 4. Development of GHG emissions from 2010 to 2050 in the TRANS and the REF scenarios.

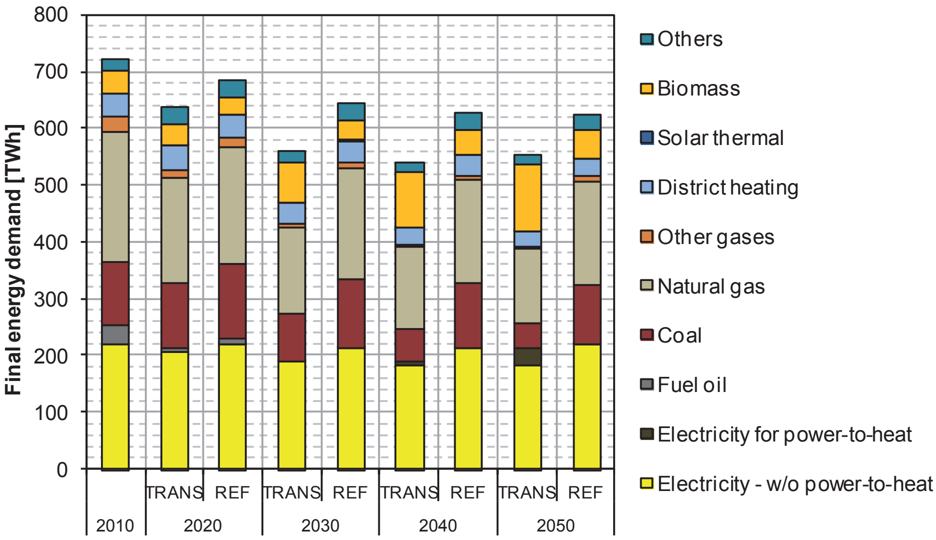

Figure 5. Total energy consumption in industry by 2050 in both scenarios by type of fuel.

although slowly. Biomass is slowly increasing in importance, while other gases and fuel oil are decreasing. Power-to-heat only gains a marginal share and arrives at about 2 TWh in 2050.

The TRANS scenario experiences a faster reduction of FED, particularly until 2040, after which a slight increase is observed. In total, FED is "only" 12 % lower in the TRANS scenario in 2050 than in the REF scenario. Reasons are among others the additional energy demand for CCS of about 28 TWh in 2050 as well as the high share of CHP in the REF scenario that reaches 68 TWh in 2050 in comparison to 15 TWh in the TRANS scenario. CHP typically has a lower FED per output and thus reduces total FED in the REF scenario.

Total electricity demand remains relatively constant in both scenarios, despite large efficiency gains particularly in the TRANS scenario. The same scenario, however, also shows a substantial increase in power-to-heat which consumes 29 TWh in 2050. This electrification of heat supply represents nearly 15 % of the total electricity demand in 2050.

Other energy carriers experience a more dramatic change in the TRANS scenario. With 132 TWh natural gas remains the second largest energy carrier after electricity in 2050, although its use falls by 42 % from 2010 to 2050. The use of biomass increases from 2010 to 2050 by about 211 % and arrives at 120 TWh in 2050.[5] Fuel oil is completely phased. Coal falls

5. For biomass we assume specific CO_2-emissions of about 7 g/kWh final energy used. These are related to methane leakage during production and transport. Biomass supply is based on domestic resources only taking into account the available potentials as well as use from agriculture.

by 62 % and only remains prominent where it is assumed to be technically necessary as in blast furnaces in the steel industry. To understand and interpret the contribution of energy efficiency improvement and its level of ambition the results related to energy efficiency are analyzed in the following.

The diffusion of EEMs in energy-intensive industries is summarized in Table 4. Accordingly, a substantially higher market share can be observed in all EEMs considered in the TRANS scenario. Although, none of the EEMs reaches 100 % diffusion in 2050, the resulting diffusion paths can be considered very ambitious given the long lifetime of the capital stock and the reluctance of the industry to radically invest in new technology. E.g. major innovations in the steel industry have taken at least 25 years to diffuse through the entire technology stock from the year they first entered the market (Arens, Worrell 2014).

While these technologies can all be considered radical changes, the efficiency improvement is still in the order of magnitude of maximum 10–30 % for the individual processes if a technology would be implemented completely. This already shows that there are limits to efficiency improvement in energy-intensive industries – if the system boundary is kept narrow as in this study. Incremental improvement of existing technology in energy-intensive processes probably will not achieve more than 10 % efficiency improvement, as shown by Brunke, Blesl (2014) for the German cement industry.

While individual cross-cutting technologies (CCT) like electric motors or air compressors consume a lot less energy than the aforementioned processes, due to their high numbers electric motor systems account for about 70 % of total electricity demand in industry. At the same time, the systems are often not optimized, old equipment is still in use and remaining efficiency potentials are substantial. Figure 6 shows how electricity demand in CCTs remains relatively constant at about 180 TWh in the REF scenario. Continuous efficiency improvements are offset by economic growth. The TRANS scenario on the other hand shows a substantial decrease of electricity demand of about 24 % from 2010 to 2050. This is driven partly by more ambitious MEPS but mainly by comprehensive system optimization.

The level of ambition can be illustrated when comparing the resulting electricity demand in both scenarios with the upper diffusion boundary described in the methodology section and the frozen-efficiency demand, which assumes frozen diffusion levels of 2010. Accordingly, in 2050 the frozen-efficiency case, the REF scenario, the TRANS scenario and the maximum diffusion case arrive at 219 TWh, 179 TWh, 137 TWh and 121 TWh, respectively. Thus, the TRANS scenario is already relatively close to the maximum diffusion scenario.

The resulting energy intensity development indicates that particularly the TRANS scenario accelerates efficiency improvement compared with the past 20 years (Figure 7). However, from 2030 onwards the improvement slows down. As discussed earlier this is driven by an increasing replacement of CHP via less efficient separate heat generation units and the market entry of CCS (~28 TWh in 2050). Also exploitation of efficiency potentials might reach saturation in the long term.

The importance of CHP changes over time. In the first decades, CHP is an option to reduce CO_2 emissions, as it allows for a more efficient utilisation of fossil fuels compared to separate generation of heat and power. From an economic perspective, a carbon price of approximately 30 Euro/t CO_2 is well suited to incentivise efficient utilisation of fossil fuels in CHP units. Whereas at higher prices, fossil fuels are gradually pushed out of application areas in which relatively cheap alternatives exists. With increasing carbon prices and rising shares of renewable energy in the power sector, the number of hours in which electricity from CHP plants can make a profit contribution decreases substantially. Despite the fact that fossil fuels could in some cases still remain cost efficient to cover the respective heat demand, base-load electricity from fossil fuels, even if CHP, becomes uncompetitive.

Table 4. Diffusion of selected innovative process EEMs in energy-intensive industries in both scenarios in comparison as percentage of total capital stock.

EEM	Scenario	2010	2020	2030	2040	2050
Chemical pulp: black liquor gasification	REF	0	2	3	6	9
	TRANS	0	4	19	41	50
Steel: waste heat recovery from rolling	REF	0	8	24	34	37
	TRANS	0	12	39	51	53
Cement: low-carbon cements	REF	0	4	7	14	23
	TRANS	0	6	18	44	64
Aluminium: wettable cathodes	REF	0	0	3	16	26
	TRANS	0	1	8	45	72
Steel: thin slap or strip casting	REF	0	7	18	21	22
	TRANS	0	10	28	33	34
Aluminium: inert anodes	REF	0	1	3	5	7
	TRANS	0	4	26	56	65
Steel: coke dry quenching	REF	0	1	1	2	3
	TRANS	0	3	14	36	45

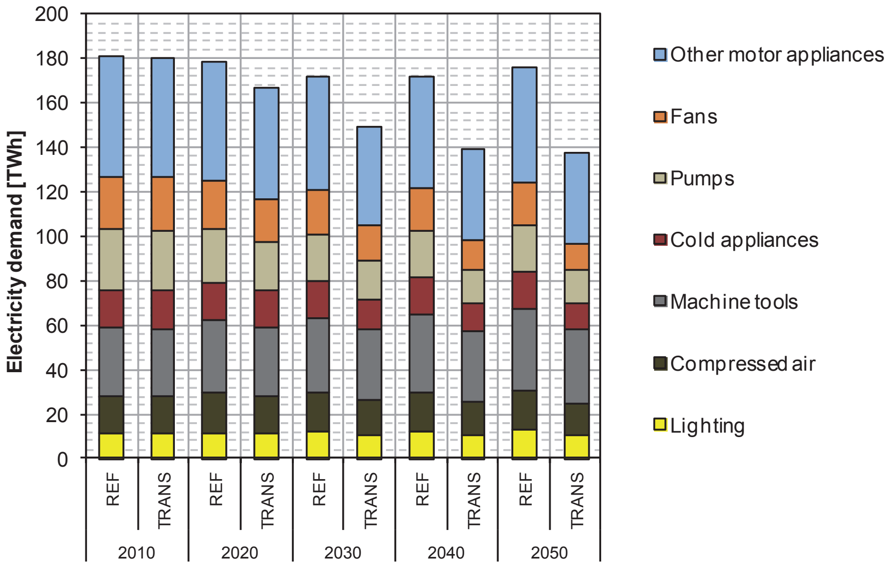

Figure 6. Electricity consumption in cross-cutting technologies by 2050 in REF and TRANS scenarios.

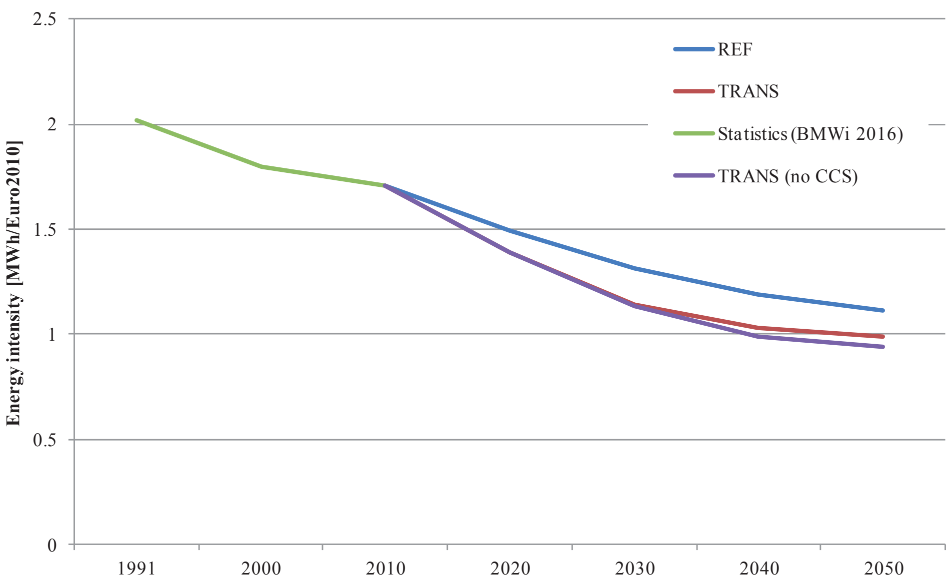

Figure 7. Energy intensity from 1991 to 2050 in both scenarios in comparison in MWh final energy demand per Euro2010 of industrial gross value added (1990–2010: historical data; 2010–2050: model results).

Summary and conclusions

We calculated an energy transition scenario (TRANS) that aims to achieve at least an 80 % reduction of GHGs in the German industry and compare it to a reference scenario (REF) that represents a world with continuation of past trends. While the REF scenario describes a continuous change that started in the past, the TRANS scenario shows a substantial change that is ranging between evolutionary and radical depending on the technology field. The TRANS scenario reached a reduction of 83 % of GHG emissions compared to 1990, while the REF scenario arrived at 50 %. The TRANS scenario sees a lot more biomass while coal is only used in the steel industry, additional use of electricity for heat generation (power-to-heat), CCS for large point sources and an exploitation of efficiency potentials. Compared to 2010, energy demand falls by 13 % in the REF scenario and by 23 % in the TRANS scenario until 2050. Thus, even in an ambitious transition scenario the industrial sector consumes substantial amounts of energy and additional mitigation strategies are required.

To achieve the assumed exploitation of **energy efficiency potentials** a lot more ambitious policies than implemented today will be needed. For **energy-intensive processes** new production processes enter the market and achieve relatively high shares by 2050. These include low-carbon cement types, thin slap or strip casting in steel production, oxygen depolarized cathode for chlorine production, innovative paper drying techniques and magnetic billet heating for extruding of aluminium. This assumption contains high uncertainty, because its success will depend on the technical development in the coming years. Also energy-efficiency potentials related to **cross-cutting technologies** (electric motor systems, lighting, steam systems) are assumed to be comprehensively exploited by 2050. While in this field the technologies needed are mostly available, the challenge is effectively addressing potentials that require broader system optimization. Mostly, production systems require individual assessments and solutions making it difficult for policy instruments to tackle them.

The TRANS scenario also shows a substantial increase towards higher **secondary production** which is one element of a **circular economy**. The share of electric steel based on steel scrap in total steel production is increasing from 29 % in 2010 to 57 % in 2050 in the TRANS scenario while it increases to 42 % in the REF scenario (assuming only domestically available scrap). Although, this includes a substantial change in the steel industry, it will remain the major coal consumer as the remaining steel is produced via the classical oxygen steel production route. Still, including the full potential of circular economy, material efficiency and industrial symbiosis into energy system models is an issue of further research. The potential contribution and even more the mitigation costs are still mostly unknown, mainly due to the huge diversity of this area.

Power-to-heat plays an increasingly important role in the TRANS scenario from 2040 onwards and increases to 29 TWh in 2050. It mainly replaces combined-heat-and-power (CHP) that shows substantial shares until 2030. In the REF scenario, CHP remains on a high level until 2050 and is only marginally replaced by power-to-heat (2 TWh in 2050).

Natural gas is also in the TRANS scenario the second most important energy carrier in 2050, although in total terms it is reduced by 49 % from 2010 to 2050. Other fossil fuels like coal or heating oil completely phase out – with the exception of coal used in the steel industry.

Biomass is increasing in both scenarios. The TRANS scenario shows an increase by 211 % to 120 TWh in 2050. This fast increase reflects the fact that biomass is a mitigation option that requires relatively little change in existing systems and can provide high temperature heat, which many renewable solutions cannot. Other renewables such as, for example, **solar thermal energy** only reaches low shares. Several reasons restrict the use in industry including the low energy density, the non-flexibility and the low temperature level, while there are certainly some niche markets. Lauterbach et al. (2012) for example estimate a technical potential of solar thermal energy at 17 TWh in the German industry.

While **carbon capture and storage (CCS)** is not used in the REF scenario, it is a major abatement option in the TRANS scenario for point sources in steel, clinker, lime, ammonia, ethylene and methanol production. The diffusion of CCS begins in 2030 and reaches a maximum for most processes except clinker in 2050. The annual sequestration CO_2 mitigation of CCS amounts to 35 Mt CO_2 in 2050. Without the use of CCS, radical innovations would have been necessary in energy-intensive production processes to achieve similar mitigation levels. For steel production, direct reduction in combination with hydrogen produced from renewable sources could become an important option (Fischedick et al. 2014). Renewable energy based hydrogen would also be needed to replace the current use of natural gas based hydrogen that is used in ammonia and methanol production in the chemical industry.

A major factor to take into account for the transition of the industrial energy consumption is the **long lifetime of the capital stock** and the often saturated markets in Germany – especially for energy-intensive products. A radical change to new processes can only take place when existing plants are being replaced. This investment cycle, however, takes very long in most processes and slows down the speed of change. From this background, it is necessary to set incentives towards low-carbon technologies as early as possible to accelerate the market entry of innovative processes. This is even more necessary when looking at the many market entry barriers for the individual innovations, as for example Dewald, Achternbosch (2015) have done for low-carbon cement innovations. They found that also standardization, market concentration, focus of public funding, R&D focussing on incremental improvements and more reasons can delay market entry substantially.

This is very relevant for CO_2 prices. The increase that takes place after 2040 only affects a smaller share of most investment decision taken. Although EUA prices increase to 100 Euro/t CO_2 by 2050, this late increase does not affect investment and R&I decisions taken in the coming two decades. More certainty with regard to the CO_2 price path could allow investors to anticipate higher future CO_2 prices and accelerate the diffusion of low-carbon technologies.

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