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Long-term model-based projections of energy use and CO_2 emissions from the global steel and cement industries

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ABSTRACT

This paper presents a global simulation-model for the steel and cement industries. The model covers the full modelling chain from economic activity, to materials consumption, trade, technology choice, production capacity, energy use and CO_2 emissions. Without climate policy, the future projections based on the SSP2 scenario show a rapid increase in the consumption of steel and cement over the next few decades, after which demand levels are projected to stabilize. This implies that over the scenario period, CO_2 emissions are projected to peak in the next decades followed by a decrease below 2010 levels in 2050. There is considerable scope to mitigate CO_2 emissions from steel and cement industries, leading to resp. 80–90% and 40–80% reduction below 2010 in 2050 for a high carbon tax of 100 $/t$CO_2$ + 4%pa depending on the availability of Carbon Capture and Sequestration (CCS).

1. Introduction

The heavy industry sector, such as steel and cement production, is a major source of greenhouse gas emissions. Together, the steel and cement industries accounted for 8% of global energy use and 15% of global anthropogenic CO_2 emissions in 2012 (IEA, 2015). Moreover, the emissions of these sectors have increased rapidly between 1980 and 2010. Growth rates between 2 and 4% per year (Saygin, 2012) were driven by a rapid increase in global demand from various sectors of the economy such as automotive and construction. In the 1980–2010 period, the global production of steel and cement nearly doubled and more than tripled, respectively. A large share of this growth is related to increased production in China: nearly 90% of the increase in global steel production emissions occurred in China (World Steel Association, 2015). Although demand in China has recently slowed down and is expected to do so further (World Steel Association, 2015), in other developing regions ongoing industrialization may still lead to rapid growth in steel demand over the next decades. Therefore understanding consumption and production trends of steel and cement is important for gaining insights into future energy use developments and related greenhouse gas emissions and the potential for mitigation. Specifically, this paper aims to answer how future demand for these materials may develop and which technologies are used in scenarios with and without climate policy.

Several modeling studies exist that project consumption, energy use and emissions from the global steel and cement sectors (Akashi et al., 2011; Allwood et al., 2010; Hidalgo et al., 2005; IEA, 2008, 2012, 2015). Most of these models are sector specific and focus on changes of production and technology choice in the steel and cement sectors. This paper presents a global model for the projection of consumption and production of steel and cement, which is embedded in the IMAGE global integrated assessment model for energy and land use changes. This model is used to analyze long-term trends in energy use, greenhouse gas emissions, mitigation and trade-offs between different mitigation options. Embedding the steel and cement sectors within the context of a global energy model provides consistency in the global energy projection (such as fuel choices, prices changes, depletion of resources) and enables analyzing synergies and trade-offs between technology measures in different sectors. A detailed description of this model, the data sources and the considerations can be found in Neelis and Patel (2006) for steel, Roorda (2006) for cement and Boskaljon (2010) for the implementation in the IMAGE model. In this paper, we describe

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the model and derive scenarios for the Second Shared Socioeconomic Pathway (SSP2) scenario (a medium development scenario) (O'Neill et al., 2014) and related mitigation scenarios. We explore future projections for steel and cement consumption, energy use and CO_2 emissions under scenarios with and without carbon taxes (i.e. with and without climate policy) and with and without the availability of CCS technology.

In this paper, we first provide an overview of the existing literature on heavy industry emissions and reduction potentials (Section 2). We analyze relations between economic activity and demand for materials and describe the global model for steel and cement consumption and production and its main assumptions (Section 3). Section 4 presents the results for baseline scenario projections and emission mitigation at different levels of carbon taxes and compares these to the existing literature. Finally, Section 5 discusses uncertainties and open issues and Section 6 concludes.

2. Literature on steel and cement models

In the past years, several models have been developed to describe regional and global energy use related to the production of steel and cement. The more detailed of these models are physical bottom-up models that are based on a description of material flows (Brunke and Blesl, 2014; Chen et al., 2014; Dutta and Mukherjee, 2010; Gielen and Moriguchi, 2002; Karali et al., 2014; Ke et al., 2012; Kesicki and Yanagisawa, 2015; Oda et al., 2009, 2007; Wang et al., 2007; Wen et al., 2015, 2014). In these models, energy requirements are being modeled in physical units (e.g. tonne of iron ore and coke needed per tonne of pig iron) and (many) technologies or aspects of the steel and cement production processes are explicitly represented. In contrast to the bottom-up models, there are also macro-economic models that describe steel production in terms of monetary parameters (CPB, 1999; Paltsev et al., 2005; Zhou et al., 2013) or econometric models and scenario approaches that describe relations between socioeconomic indicators and material demand energy use and emissions (Milford et al., 2013; Rootzén and Johnsson, 2013). There are also several models that describe the steel and cement sectors together with others such as petrochemicals or pulp and paper (Aden, 2010; Akashi et al., 2011; Dutta and Mukherjee, 2010; Graus et al., 2011; Oda et al., 2007). The main aim of all models mentioned here is to describe future demand and production volumes and the resulting energy use and CO_2 emissions in a given time frame.

Key production technologies included in steel production models are the blast furnace (BF) and technologies to produce direct reduced iron (DRI) for hot metal production combined with steel making technologies, such as basic oxygen furnace (BOF) or electric arc furnace (EAF). Recently, models include also recycling and material efficiency improvement as processes to reduce energy use and greenhouse gas emissions (Aden, 2010; Chen et al., 2014; IEA, 2015; Karali et al., 2014; Michaelis and Jackson, 2000; Milford et al., 2013; Oda et al., 2007).

Cement production models include (at different levels of detail) wet or dry kilns for clinker production and roller or ball mills for cement grinding. Also, some models explicitly consider several different types of cement such as fly ash, blast furnace slag or Portland cement (Wen et al., 2015). In all models, cement types and production technologies compete with each other for market share based on production costs. Recycling is not considered for cement since (cementitious) demolition waste is of lower value and is mostly used as gravel for roads and other infrastructure. Only several models include retrofit measures for energy efficiency improvement (e.g. Corsten, 2009), though for both steel and cement there is a separate body of literature on emission reduction cost curves (Li and Zhu, 2014; Morrow et al., 2014; Moya and Pardo, 2013).

Only a few large-scale models account for material efficiency improvements through product life extension or material substitution (e.g. Allwood et al., 2010), or include the option of reducing losses in production processes (e.g. improving yields in sintering, steel making or hot rolling) (e.g. Milford et al., 2011; WSA, 2009). Also, decreasing ore availability and purity and the related additional energy used are only in some cases considered (see e.g. studies by Allwood et al., 2010 for bauxite prodiuction; Harmsen et al., 2013 for copper production; van Vuuren et al., 1999; Yellishetty et al., 2010 for iron ore). An increasing number of studies for cement consider clinker substitution by alternative materials (e.g. Anand et al., 2006; IEA, 2008, 2009, 2010, 2012, 2015; Wen et al., 2015). Modeling of more fundamental alternative strategies for material efficiency improvement or structural changes in end use of materials is scarce. Finally, for both steel and cement only a handful models include the potentials of carbon capture and storage (CCS) technology (e.g. Gielen, 2003; Gielen and Moriguchi, 2002; Moya et al., 2011; Oda et al., 2009; Wang et al., 2014).

Physical demand for steel and cement is in many models linked to economic activity in the form of GDP (e.g Aden, 2010; Akashi et al., 2011; Anand et al., 2006; Dutta and Mukherjee, 2010; Groenenberg et al., 2005; Zhou et al., 2013) or industrial value added (Kesicki and Yanagisawa, 2015) and population growth. Some models take demand as completely exogenous (Karali et al., 2014; Rootzén and Johnsson, 2013; Wen et al., 2015, 2014). Models that focus on a single region, often ignore trade of materials or keep import and export shares constant (e.g. Allwood et al., 2010; Anand et al., 2006; Chen et al., 2014; Wen et al., 2015, 2014). An exception is the study by Akashi et al. (2011) which uses a partial equilibrium model that balances domestic and international demand and supply of iron and steel. Also, macro-economic approaches (CPB, 1999; Paltsev et al., 2005) and other global models (Zhou et al., 2013) inherently include dynamics of trade. In several other studies, trade is modeled separately (e.g. Hidalgo et al., 2005; Oda et al., 2007).

Most studies analyze energy use and CO_2 emission developments under energy and climate policies. This is either done by assuming that sectors will reach a comparable technology level as a result of such policies within a certain time frame (e.g. Graus et al., 2011; Groenenberg et al., 1999) or by quantifying the effects of specific policies (Hidalgo et al., 2005). Several studies also quantify the abatement costs of technologies for steel and cement making or the additional costs of climate policies compared to the level of the frozen efficiency or a reference scenario (Corsten, 2009; Gielen, 2003; Wang et al., 2007).

Concluding, it can be observed that regional models generally offer a bottom-up approach with detailed technology representation, whereas global models are more generic and top-down oriented. The global models do include trade and embedding of the steel and cement sectors in the global energy system, whereas regional models often neglect trade and only integrate industry and energy at the regional level. The literature does not yet include an equivalent to the model presented here: a relatively detailed bottom–up steel and cement model embedded in a global integrated assessment model.

3. Method

3.1. Context: the IMAGE energy model

The Timer IMAGE energy system simulation model (TIMER) describes the long-term dynamics of the production and consumption of 10 primary energy carriers for 5 end-use sectors in 26 world regions (de Vries et al., 2001; van Vuuren et al., 2007, 2014). Aggregate demand for energy is derived from changes in useful energy

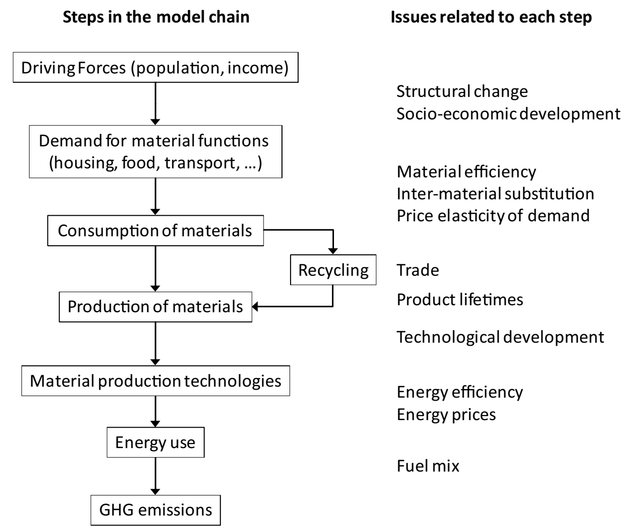

Fig. 1. overview of material modeling in IMAGE. Steps on the left represent explicit steps in modeling material demand, consumption and production, whereas the right column indicates which issues are relevant in each model step.

intensity of economic activity, with autonomous and price-induced energy efficiency increases. In energy demand, an attempt is made to add technology and activity explicit formulation such in the residential sector (Daioglou et al., 2012; van Ruijven et al., 2012, 2011), transport (Girod et al., 2012; Girod et al., 2013) and industry sectors (this paper).

For energy supply, the model uses a set of multinomial logit models that describe investments into new energy production capacity.[1] The long-term prices that drive these logit equations are determined by resource depletion and technology development. Resource depletion is important both for fossil fuels and for renewables. While for fossil fuels, depletion is driven by cumulative production depleting resources, for renewables depletion and costs depend on annual production rates and siting. Technology development is determined by learning-curves or through exogenous assumptions. Emissions from the energy system are calculated by multiplying energy consumption and production flows with emission factors, based the EDGAR 4.1 database (EC-JRC/PBL, 2011). A carbon tax can be used to induce a dynamic response such as increased use of low or zero-carbon technologies, energy efficiency improvement and end-of-pipe emission reduction technologies.

3.2. Overview of materials modeling

The approach to modeling steel and cement in IMAGE (Fig. 1) starts with simulating the physical demand for materials, based on statistical relations between economic activity and material intensity, and the demand for steel and cement. Next, a material production model simulates how to fulfill the demand for steel and cement. This submodel takes into account dynamics such as trade, production stock turnover, material recycling, and competition between different steel and cement production technologies. Finally, based on the technology mix and energy prices, the final energy use is determined, from which greenhouse gas emissions can be derived.

[1] A multinomial logit model assigns market shares to fuel or technologies based on their relative costs. Low costs options get a large market share; high costs options a low (or even zero) market share.

3.2.1. Demand for steel and cement

For the long-term projections, consumption of materials is described as function of per capita economic activity. We collected data on production and trade for the period 1970–2012 for steel and 1970–2010 for cement to derive such relationships. Detailed references for data prior to 2003 can be found in Neelis and Patel (2006) and Roorda (2006), while recent steel data have been obtained from the World Steel Association (2013). Cement production data are from the United Nations Statistics Division (2013). Data on GDP per capita were taken from World Bank (2014). We derived apparent consumption data from production and net trade.

We evaluated several alternative models to identify the best representation of patterns in historic data. The simplest models are linearized regression models that relate economic activity (GDP per capita) to material consumption per capita (C) (Tanaka, 2010):

- Log-log (LL): $\ln C = a + b \ln GDPpc$
- Semi-log (SL): $C = a + b \ln GDPpc$
- Log-inverse (LI): $\ln C = a - b/GDPpc$
- Log-log-inverse (LLI): $\ln C = a - b/GDPpc - d \ln GDPpc$
- Log-log-square (LLS): $\ln C = a + b \ln GDPpc - d \ln GDPpc^2$

in which a, b and d are constants to be estimated in the regression. In addition, we analyzed a non-linear model (NLI) with an S-shaped relation between GDP per capita and material consumption (also discussed in detail in Neelis and Patel (2006) and Roorda (2006)) and a variant in which per capita material demand is reduced over time as result of efficiency improvement (NLIT). We also analyzed a linearized version of the latter model (LIT):

- Non-linear inverse (NLI): $C = a \times e^{(B/GDP)}$
- Non-linear inverse with time-efficiency-factor (NLIT): $C = a \times e^{(B/GDP)} \times (1\text{-}m)^{(T-2010)}$
- Log-inverse with time-efficiency-factor (LIT): $\ln C = a + b/GDP + \ln(T\text{-}1969)$

We performed regression analysis for steel and cement for all models at the global level, aggregating data to 26 regions as defined for the IMAGE model (Stehfest et al., 2014). Tables 1 and 2 report both the R^2 value for the linear models and the root mean square error (RMSE) on per capita consumption values for all models. Note that the R2 values for the linear models are not all comparable, since some are for absolute consumption levels and others for the ln(C). For both steel and cement, the nonlinear models stand out with the best fit to historic data (in terms of the RMSE for per capita consumption). For steel, the model assuming a 1% per year efficiency improvement of per capita consumption has a better fit than the models without improvements over time. For Cement, the NLI and NLIT models are very comparable, especially since the value of the time-related efficiency improvement in NLIT is zero.

Based on this analysis, we use for steel consumption the global NLIT model as starting point and derived individual curves for some major steel consuming regions (Fig. 2). For the five regions (Canada, USA, Western Europe, Japan and Oceania) that have per capita GDP levels above 20,000 2005 ppp $ in 2012, we kept the maximum in the per capita consumption (PCC) curve (parameter −b) equal to the global curve. We calibrated the per capita saturation level (parameter a) such that the resulting per capita consumption level in 2012 equals the data. For China and the Ukraine+ region, which currently have per capita consumption levels well above the global curve at low per capita income levels, we kept the per capita saturation level (parameter a) equal to the global curve and calibrate the maximum in the PCC curve (parameter −b) such that per capita consumption equals data in 2012. For Korea, currently having at a per capita income of 19980 2005 ppp $ already a per capita con-

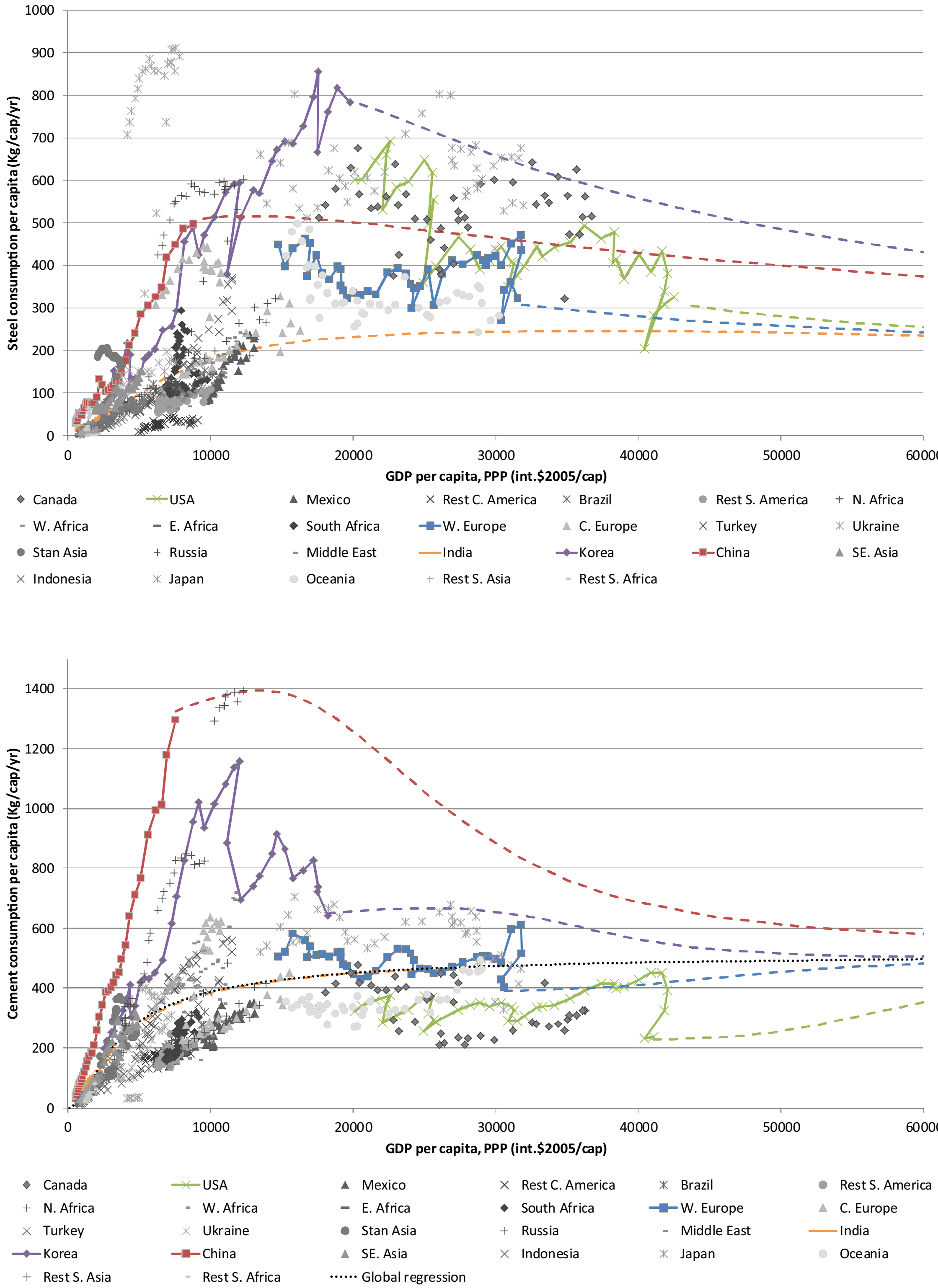

Fig. 2. Per capita consumption of steel (top) and cement (bottom) vs. GDP per capita. Historical data shown for 26 world regions for the period 1970–2012. Five major regions are highlighted, USA, Western Europe, Korea, India and China, each with baseline projections of per capita steel consumption in dotted lines. The black dotted line for cement represents the global regression.

Table 1
comparison of regression models for per capita consumption (C) of steel for all 26 IMAGE regions for the period 1970–2012. In these formulas C is per capita consumption, GDP is GDP per capita and T represents time.

Linear Models								Nonlinear models	
Model	LL	SL	LI	LLI	LLS	LIT		NLIT	NLI
Formula	ln(C) = a + b × ln(GDP)	C = a + b × ln(GDP)	Ln(C) = a- b/GDP	Ln(C) = a- b/GDP + d × ln(GDP)	Ln(C) = a+B × ln(GDP) − d × ln(GDP)^2	Ln(C) = a + b/GDP + d × ln(T-1969)		C = a × e$^{(b/GDP)}$ × (1-m)$^{(T-2010)}$	C = a × e$^{(b/GDP)}$
Intercept	−6.1	−999	5.5	−4.5	−6.1	6.1	a	634.7	713.2
Coef1	1.2	137	−3548	−569	1.2	−3634	b	−11891	−11079
Coef2				1.05		−0.18	m	0.01	
R^2	0.77	0.6	0.66	0.77	0.77	0.67			
RMSE (C)	133	122	156	122	133	155		101	106

Table 2
comparison of regression models for per capita consumption (C) of cement for all 26 IMAGE regions for the period 1970–2010. In these formulas C is per capita consumption, GDP is GDP per capita and T represents time.

Linear Models								Nonlinear models	
Model	LL	SL	LI	LLI	LLS	LIT		NLIT	NLI
Formula	ln(C) = a+ b × ln(GDP)	C = a+ b × ln(GDP)	Ln(C) = a- b/GDP	Ln(C) = a- b/GDP + d × ln(GDP)	Ln(C) = a+ B × ln(GDP) − d × ln(GDP)^2	Ln(C) = a + b/ GDP + d × ln(T-1969)		C = a × e$^{(b/GDP)}$ × (1-m)$^{(T-2010)}$	C = a × e$^{(b/GDP)}$
A	−1.6	−840	6	3.6	−1.6	5.9	a	522	487
B	0.8	127	−2550	−1843	0.8	−2538	b	−2980	−3047
D				0.25		0.03	m	0	
R^2	0.72	0.48	0.78	0.8	0.72	0.78			
RMSE (C)	182	147	150	150	183	150		144	145

sumption above the saturation level of the global curve, we assume a final per capita saturation level (parameter a) equal to Japan. The maximum in the intensity of use curve (parameter −b) is then calibrated using the same method as used for China+ and the Ukraine+ region. For all other regions, we use a Gompertz curve to smooth out deviations between historic data and the per capita consumption (PCC) curve. The final formulation of steel consumption is:

$$PCC_t = a \times e^{\frac{-b}{GDPpc_t}} \times (1-m)^{(t-2010)} + \left(\Delta_{2010} - \Delta_{2010} \times e^{-\phi \cdot e^{-\mu \cdot (t-2005)}}\right)$$

In this, a and b are the estimated parameter from Table 1, Δ_{2010} is the deviation between actual and estimated per capita consumption in 2010 and μ and φ are Gompertz parameters with values chosen to remove the deviation over a period of 50 years.[2]

For cement consumption we use the values from the global NLI model and assume that all regions converge towards the globally derived consumption curve by 2060 (Table 1, Fig. 2). Some regions are historically close to this curve, such as India, Western Europe and the USA, while other regions have higher historic consumption, such as China and Korea (Fig. 2). We use a Gompertz curve as described above to smooth out deviations between historic data and the PCC curve.

3.2.2. Model structure for production of steel and cement

3.2.2.1. Vintage stock turnover. We assume that all demand for steel and cement is fulfilled, either through domestic production or trade with other regions. We use a vintage capital stock model to simulate the development of steel and cement producing capital stock over time. In case of declining demand, we assume that production is reduced proportionally for all plants.[3]

Investment costs are a relatively large part of production costs of steel and cement plants and it is usually cheaper to use an existing facility than building a new one. We assume that all factories are used until the end of their technical lifetime (40 years), which brings inertia into the model.

3.2.2.2. Specific energy consumption. For each steel and cement production technology, we assume a Specific Energy Consumption (SEC): the amount of energy that is needed to produce a ton of the respective material. This SEC is historically derived from data and literature and assumed to improve over time. We make assumptions on the future rate of efficiency improvement based on literature (Gielen et al., 1998; Groenenberg, 2002; IEA, 2009; Neelis and Patel, 2006) and generalize this function as follows:

$$SEC = \alpha(\varepsilon)^{t-2010} \quad (5)$$

ε = Efficiency improvement every year (%/yr) (see Table 4 and 5 for assumptions).α = Specific Energy Consumption in the year 2010 (in gigajoules (GJ) per tonne of material).t = year for which SEC is calculated.

The IMAGE model simulates historic energy use for all sectors and regions from 1971 to 2007, before calculating scenarios forward into the future. For the historical period, we assume that factories have a marginal energy intensity (SEC) at the moment of being built that equals the observed average historic SEC of the entire capital stock fifteen years later. The model has been run with this assumption and the error of total energy use per sector was within 10% of historic data.

The SEC values used in this study represent only energy use in the factory, defining the system boundaries of SEC values as "factory gate-to-factory gate". This excludes energy use related to the production of raw materials, which could be relevant due to gradually decreasing ore quantities. For copper, Harmsen et al. (2013) show that in the case of ambitious implementation of renewable energy, the cumulative energy use across the process chain increases by a factor of 2–7 depending on technological progress, the recycling rate and the future electricity demand. van Vuuren et al. (1999) looked into this earlier suggesting a somewhat smaller impact, and indicating also that ore depletion will not be very important for future energy demand for primary steel.

[2] Values for φ are 9 and 10 for steel and cement respectively, and μ is 0.1 for both materials

[3] In the future projections presented in this paper, no forced reduction of production stock takes place, as all reductions of demand can be captured by the assumed depreciation rate.

3.2.2.3. Multinomial logit market allocation. Throughout the energy model for IMAGE, multinomial logit formulations are used to allocate market shares of new investments:

$$S_i = \frac{e^{-\lambda c_i}}{\sum_{i=1}^{n} e^{-\lambda c_i}} \tag{6}$$

Where:- S_i = the share of option *i*- c_i = cost of option *i* in $/tonne (or $/GJ for energy carriers)- λ = Logit Factor- n = the number of options

This equation basically assigns the largest share in investments to options with relatively lowest costs. The logit factor λ represents the cross-price elasticity and determines how "sensitive" the function responds to price differences between options. The larger the value of λ the stronger impact price differences have on the market allocation. The value of λ is based on calibrating the model to historical cost differences and market shares.[4]

The allocation of energy carriers and production technologies takes place in two steps of nested multinomial logit formulations. First, the share of energy carriers for each production technology is determined. For steel and cement production technologies without preference for certain energy carriers, such as cement kilns, we assume the allocation of energy carriers to each technology is only based on energy prices. Other technologies, however, are restricted to certain energy carriers, such as an EAF for steel production that require a minimum share of electricity. For these technologies, minimum shares of certain energy carriers are prescribed, whereas the remaining share is filled by cost-based allocations. After allocating energy carriers, the costs of production from each technology can be determined, and market allocation is done for technologies.

The total costs of the different production technologies include energy costs (based on the energy carrier allocation above), annualized investment cost, O&M cost and in case of cement potentially carbon taxes for process emissions. Production technologies are allocated based on the total costs to produce a tonne of steel or cement.

3.2.2.4. Trade. Trade is modeled through dedicating new investments in production capacity to specific world regions. This capacity remains dedicated to produce for a specific region for its entire lifetime. Once market shares for technologies have been assigned, the model determines in which region to build new production capacity. The main drivers of trade between regions in this model are the relative production costs per region, the transport costs between the main ports of the two regions, and a trade barrier factor between regions based on historic trade data and scenario assumptions (e.g. increased or decreased openness of economies). As most cost-components do not differ across regions, the regional production levels are mainly driven by the costs of trade and regional energy prices. Also here, a multinomial logit formulation is used, based on the average production cost in regions. Based on historic observations, we assumed that there is a strong preference to produce steel and cement within the region itself and limited amounts are traded internationally.

3.2.2.5. Steel recycling. Several steel producing technologies can use scrap as input material. However, the use of scrap is limited by supply and the required quality of steel for a certain application. To determine the available scrap, we use an explicit formulation of the flow of steel through the economy see also Neelis and Patel (2006). It should be noted that even if abundant scrap is available,

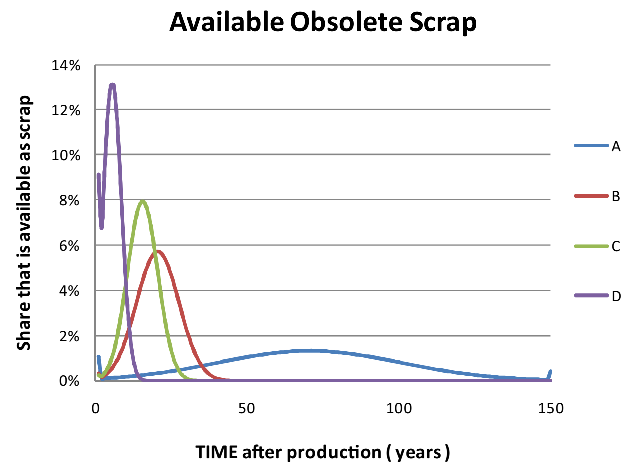

Fig. 3. Graphical overview of the availability of the different groups in the obsolete scrap model. It shows the percentage of the total amount that is available after a number of years. The spikes at the beginning and end of the lines capture the amount that falls outside the time interval 1–150 years (Neelis and Patel, 2006).

we assume a maximum share of EAF in steel production of 90% in order to account for the higher steel quality required for several products (after Kopfle and Hunter, 2008).

In the scrap model, we assume three types of scrap: metal that is lost during the production of the metal itself (circulating scrap), metal that is lost during the production of goods (prompt scrap) and scrap that is available after the lifetime of the goods (obsolete scrap). The circulating scrap is assumed to be part of the steel production process, because nearly all of it is recycled and it never leaves the system boundaries of the steel plant. We assume that prompt scrap is available for recycling immediately, with a recycle rate of 70%. Obsolete scrap is determined by identifying 4 types of steel uses, each with a typical lifetime in society. After steel in each of these use types has reached the associated lifetime (starting from the production year), it is available again to be recycled. The representative examples for each of the four product groups are 1) construction, 2) machinery, 3) cars and 4) soda cans. Table 3 gives more information of the product groups and Fig. 3 shows the availability for recycling of the different product groups in the years after they have been produced. The recycle rate of metal that becomes available to use as obsolete scrap is assumed 70% (Neelis and Patel, 2006). Scrap is not traded internationally in this model. One reason is that it would require determining a regional scrap price – for which we did not find enough information to include this in the model.

3.3. Technologies and assumptions for producing steel and cement

The model structure for producing steel and cement, described above, is flexible to be parameterized with assumptions for several different technologies. We made assumptions to simulate several major technologies and expected developments over the next decades, but since many different routes are available to produce steel and cement, difference choices can be made. In both sectors, we distinguish between "standard" technologies and "efficient" technologies for the currently dominant production methods, where efficient means that all currently available efficiency improvements are implemented.

3.3.1. Assumptions on iron and steel technologies

The iron and steel production model includes eight production routes (Table 4) that consist of combinations of coal blast furnace (BF), Basic Oxygen Furnace (BOF), direct reduced iron production

[4] Based on analysis of historic energy and technology choices, the value of λ is assumed 0.5 for steel production and 0.8 for cement production technologies. For allocating different energy carriers, the value is 1.5 for both sectors.

Table 3
Overview of the product groups used in for obsolete scrap.

Group	A	B	C	D
Representative for:	Construction	Machinery	Cars	Cans
Assumed share in Steel Consumption	35%	25%	25%	15%
Assumed average Lifetime	70 years	20 years	15 years	5 years
Assumed standard deviation	30 years	7 years	5 years	3 years

Table 4
Assumptions on costs, energy use and CCS of steel production plants.

	Investment costs ($/tonne production capacity/yr)	Annual O&M costs ($/tonne production capacity)	SEC in 2010 (GJ/tonne) (α in Eq. (5)	Energy efficiency improvement (%/yr) (ε)	CO_2 captured	Effective operation time
Coal BF + BOF	$471	$89	20.4	0.9%	0%	95%
Efficient coal BF + BOF	$563	$89	18.6	1.0%	0%	95%
Coal BF + BOF + CCS	$623	$89	18.6	0.9%	80%	95%
DRI + EAF	$372	$58	19.8	0.9%	0%	95%
DRI + EAF + CCS	$412	$58	19.8	0.9%	80%	95%
Scrap EAF	$230	$46	8.0	0.9%	0%	95%
COREX	$441	$88	19.4	1.1%	0%	95%
COREX + CCS	$491	$88	19.4	1.1%	80%	95%

(DRI), electric arc furnace (EAF) and COREX smelt reduction. Some production routes can be combined with carbon capture and storage (CCS).

The main production route for steel is the integrated route consisting of a coke oven, sinter plant, BF and a BOF. In the coke oven, coal is heated without oxygen at high temperatures to form cokes and in a sinter plant iron ore is prepared for the iron making process. The sinter and cokes are fed into a blast furnace where molten iron is formed by separating iron from other elements. In a counter current shaft system the iron and cokes are fed at the top and oxygen-enriched hot air is blown into the bottom, heating the furnace to around 1500 °C. A basic oxygen furnace is then used to drive out carbon and other impurities that are still dissolved in the melt. This is an exogenous process and the temperature is kept constant by feeding in additional recycled steel. The resulting metal is than either further purified or alloyed, or directly brought to the casting process (Corsten, 2009). Assumptions on efficient blast furnace technology include among others modern energy monitoring and management systems, BOF gas and sensible heat recovery and continuous casting. Some of these efficiency improvements are not technical, but just related to “good housekeeping”. We assume that these measures will be implemented also for “standard” BF + BOF technology if carbon taxes are applied.

The second main technology to produce steel is by using an EAF. This furnace can be fed with either recycled metal (scrap) or iron made by direct reduction. Inside the EAF the iron is melted using electricity and metal is formed. The main advantage of an EAF over the BF-BOF route is that it can run solely on recycled steel which greatly reduces the specific energy use of the steel production process.

BF and EAF, represented in the first three options in the list above, are currently widely used. Other methods to produce iron and steel are in earlier stages of development and are expected to be commercially available according to several studies (Corsten, 2009; IEA, 2009). These include direct reduction and smelt reduction. In the direct reduction process gas is used to reduce the impurities in the iron. It is a primary production process, but has lower energy consumption than the integrated route. This process is economically viable in regions with cheap natural gas. In the smelt reduction process coal is gasified, which is then used in a direct reduction process. In our model this technology is represented by the COREX technology. This process has the low energy consumption advantage of the direct reduction process combined with the option to use cheaper coal rather than natural gas (Corsten, 2009). Smelt reduction and CCS technologies are assumed to always include all available energy efficiency improvements. We did not take into account other technologies because these are either outdated (such as the open-heart furnace) or are not likely to be commercially available at a large scale within a decade.

The costs and energy use of the steel production technologies differ with respect to many issues, such as prices for energy and labor and how advanced the technology is. Therefore it is difficult to compare studies including only one technology, because they are often based on local conditions. We used a source that contains comparable information on many technologies, the MARKAL MATTER database (Gielen et al., 1998). It contains information on all steps of the steel production process including estimates for prices and energy use under generalized conditions. The steps have been combined into complete chains of production, obtaining estimates for future costs for investment and O&M. This information was updated with recent sources to check for inconsistencies and more recent insights (Corsten, 2009; IEA, 2009; Neelis and Patel, 2006; Roorda, 2006), see Table 4.

3.3.2. Assumptions on cement production technologies

We use Portland cement as reference definition for cement, since it is the most used cement and its standards are internationally defined (Comité Européen de Normalisation (CEN), 2000; WBCSD, 2009). It is produced by mixing clinker with other minerals such as limestone. In this research we focus on the production of clinker, although consumption is modeled for cement. One of the most important processes in clinker production is calcination, the decomposition of $CaCO_3$ into CaO and CO_2. Not only is this process one of the main consumers of energy of the cement making process, it is also a large source for CO_2 process emissions. For every kg of cement that is produced, about 0.5 kg of CO_2 is emitted due to process emissions, which is more than half of the total emissions for an energy efficient cement plant (WBCSD, 2009).

The cement production model includes four technologies (Table 5) that consists of different dry feed rotary kilns (standard and efficient), possible combined with CCS. The default kiln route consists of raw mill, a pre-heater, a pre-calciner, a rotary kiln and a cooler, with simple exhaust heat recovery and fuel preparation. The efficient kiln is based on the standard but with improved process and fuel control systems, more efficient pre-heaters and pre calciners and an improved cooling/heat recovery system.

Table 5
assumptions on costs, energy use and emissions of cement production plants.

	Investment costs ($/tonne production capacity/yr)	Annual O&M costs ($/tonne production capacity)	SEC in 2010 (GJ/tonne) (α in Eq. (5)	Energy efficiency improvement (%/yr) (ε)	CO_2 captured	Effective operation time
Standard Dry	$193	$10	3.9	0.2%	0%	95%
Efficient Dry	$263	$10	2.9	0.6%	0%	95%
Efficient + on-site CCS	$326	$10	3.3	0.6%	55%	95%
Efficient + oxy-comb. CCS	$558	$10	8.2	0.6%	86%	95%

There is only one main production process that is currently used in new cement plants worldwide. Therefore the choice of technology is mainly a choice of what the level of technology applied is, instead of actual different production routes, as is the case for steel. Most adaptations to the production process are applied because they save energy, which is one of the main costs in the cement production process. This means that the basic new technology is already more energy efficient than many of the plants operated around the world right now. The efficient production option has some efficiency improvements, usually the more technologically advanced and more expensive versions of the ones that are used in the standard production plant. Some of these efficiency improvements are not technical, but just related to “good housekeeping”. We assume that these measures will be implemented also for “standard” cement production technology once carbon taxes are applied.

The two CCS options, both based on the efficient dry process, are technically very different. The on-site option is a post-combustion CCS as it is also envisioned for other industries, where the exhaust gasses are treated to extract CO_2. In the oxy-combustion CCS, fuel is not burned using normal air, but with a mixture of pure oxygen and exhaust gasses.[5] Because the exhaust gas stream consists of almost pure CO_2 it is directly ready for transport and storage (Barker et al., 2009).

Assumptions for costs and energy use of new cement plants are based on the MARKAL MATTER database (Gielen et al., 1998), updated based on more recent studies (Barker et al., 2009; Hendriks et al., 2002; IEA, 2009). Costs for cement plants depend heavily on local factors such as availability and prices of fuel, taxes and governmental regulations. The CCS assumptions are based on Barker et al. (2009), however, because the technology is not readily available, we assumed a linearly decreasing additional cost markup until 2030 to simulate development cost. All other costs are kept constant over time.

Although we assumed Portland cement as representative product, cement is a rather undefined mixture of clinker and various other substances such as fly ash and/or limestone. Portland cement contains usually around 95% clinker and there are often also other restrictions to its composition. It is, however, also possible to make cement of the same quality using a mixture with less than 95% clinker. Examples of materials that can be used instead of clinker are blast furnace slag and volcanic rock, the production of which consumes much less energy. With increasing energy prices, more R&D is being done to replace clinker with these other materials. Another advantage of replacing clinker is that it reduces process CO_2 emissions from clinker production. We included this option in the model by assuming that the share of clinker in cement would be reduced from the current values (between 74% – 84%, depending on national legislation) linearly to 65% with carbon prices between 27 $/t CO_2 and 270 $/t CO_2.

[5] In this case, the exhaust gasses are mainly CO_2. They are mixed with the oxygen to make sure the burning temperatures of the fuel do not rise too far above those needed for cement (about 1450 °C) which would lead to energy losses.

3.4. Scenario assumptions

As starting point for future projections, we use the Shared Socioeconomic Pathway 2 (SSP2) scenario (Chateau et al., 2015; Jiang and O’Neill, 2015; Samir and Lutz, 2015; O’Neill et al., 2015) as implemented in the IMAGE model (Van Vuuren et al., in review). In this scenario, global population increases from 6.9 billion persons in 2005 to more than 9 billion people in 2050. Global average GDP per capita, in purchasing power parity (ppp), increases from just under 10000 dollar in 2005 to around 26000 dollar by 2050. Projections for population and GDP per capita for several major world regions are shown in Table 6. In the discussion of model results, we mainly focus on the regions USA, Western Europe, China+[6] and India, which accounted together for 67% and 71% of global steel and cement production in 2010 respectively.

For the mitigation scenarios, we explore three carbon tax scenarios starting at 20, 50 and 100 $\$_{2005}$/t CO_2 in 2020 an increasing with 4% per year.

4. Future projections for the steel and cement sectors

4.1. Baseline projections

In our representation of the SSP2 scenario, the global demand for both steel and cement increases sharply in the first few decades, with a decreasing growth rate after 2030 (Fig. 4). Global steel consumption grows from 1537 in 2010–2160 Mt/yr by 2050 and the share of USA, Western Europe, China+ and India in global steel consumption declines steadily from 66% in 2010 and to 52% by 2050 as growth is faster in upcoming developing countries in Latin America, Africa and the rest of Asia. Cement consumption increases from present day 3220 Mt/yr to 4200 Mt/yr in 2050 while the share of USA, Western Europe, China+ and India in cement consumption decreases from 70% in 2010 to 48% in 2050.

4.1.1. Steel

Steel production is currently divided over standard blast furnaces and electric arc technology, with the latter dominating in the USA and Western Europe, and blast furnaces dominating in India and China (Fig. 5). Towards 2020 the model shows a slight increase of electric arc furnaces for primary steel and efficient blast furnaces. Together with scrap EAF, both these technologies dominate the baseline scenario projections for 2050 for all regions. Scrap based EAF already plays an important role in the USA and Europe, where it accounts for 75% and 66% of steel production resp., but this declines to about 60 and 50 by 2050 as consequence of reduced scrap availability and the long-term decline in per capita consumption levels. With increasing scrap availability this technology does become more prominent in India and China, growing resp. from 13% to 30% and 18% to 50% between 2010 and 2050. Globally, the share of scrap-EAF is stable around 40%. For developing countries, the shift towards scrap-based steel production leads

[6] The China+ region includes China, Hong Kong, Macao, Mongolia and Taiwan.

Table 6
Assumptions for population (Samir and Lutz, 2015) and GDP per capita (Chateau et al., 2015) for the world and several major regions in the SSP2 scenario.

		World	USA	Western Europe	China+	India
Population (million persons)	2010	6922	317	410	1380	1214
	2020	7672	342	426	1420	1377
	2050	9243	410	459	1303	1719
GDP per capita ($\$_{2005}$/per capita, PPP)	2010	9891	40502	30771	8355	2964
	2020	13585	48730	34524	17917	4991
	2050	25987	65141	50268	48528	15782

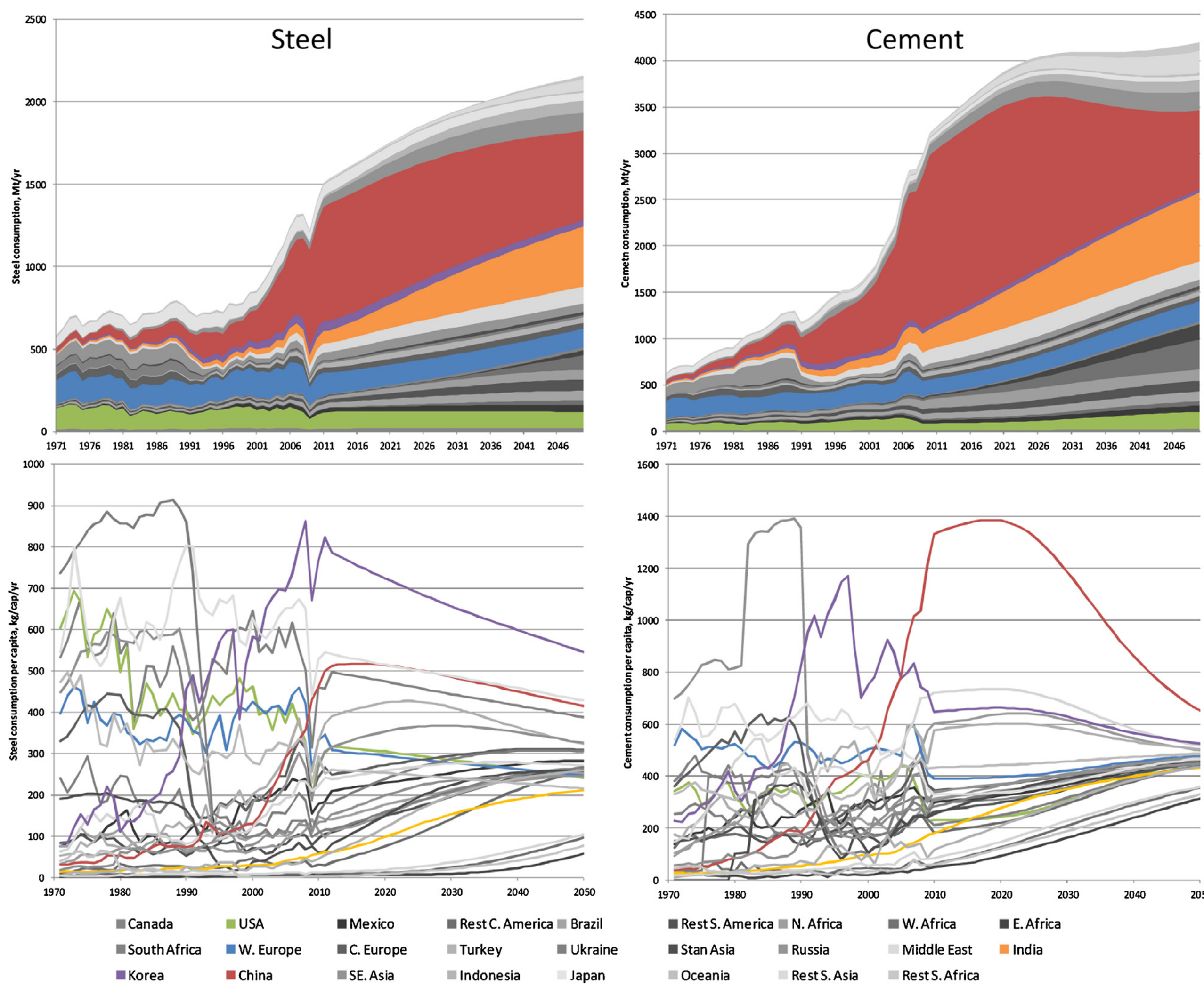

Fig. 4. Regional consumption of steel (left) and cement (right) in total (top) and per capita (bottom) terms.

to a strong reduction in energy use per tonne steel produced from around 25–30 GJ/tonne today towards 12–14 GJ/tonne by 2050, values which are observed currently in Europe and the USA (Fig. 10). A similar change occurs for carbon intensity, coming down from 2.7–2.9 tCO_2/tonne steel to around 1.2-1.4 tCO_2/tonne by 2050, comparable to current values in industrialized countries (Fig. 10). For final energy use, these changes lead to an increasing share of electricity in the steel sector and an increase in natural gas use, especially in China and India (Fig. 6). However, coal remains the dominant fuel for the steel industry in the baseline scenario without climate policy. Global CO_2 emissions from the iron and steel sector increase, from 3250 $MtCO_2$/yr in 2010–3350 MtCO2/yr in 2020, after which they decrease slowly to 2500 MtCO2/yr in 2050 (Fig. 9). Emissions are decreasing in the USA and Europe, from 150 to around 100 $MtCO_2$/yr and from 300 to around 170 $MtCO_2$/yr, respectively. Projections for steel sector emissions in China show a peak and decline, from 1660 $MtCO_2$/yr in 2010–1920 $MtCO_2$/yr in 2020 and 700 $MtCO_2$/yr in 2050. India shows a steady growth, from 160 in 2010, to 290 and 520 $MtCO_2$/yr in respectively 2020 and 2050.

4.1.2. Cement

Global clinker production increases from about 2630 Mt/yr in 2010 to 3180 Mt/yr in 2050 (Fig. 4). Currently, cement production is dominated by standard production technology for the world, and all regions (Fig. 7). In future projections without climate policies the share of efficient cement production technologies increases slightly but hardly significant. Energy use per tonne clinker does come down in all regions, though, as result of improvements in standard production technology (Fig. 11). This also leads to a slight

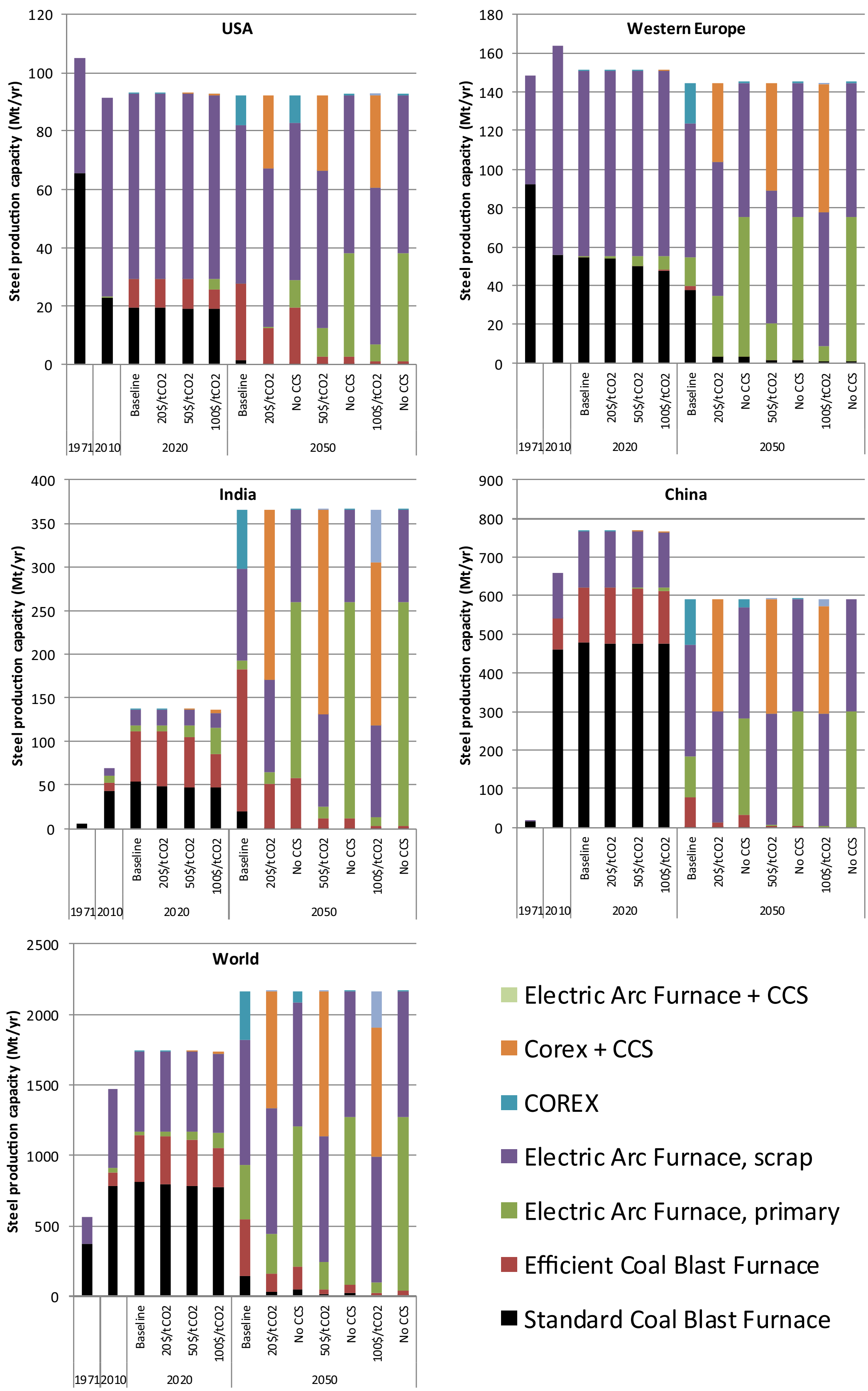

Fig. 5. Production of steel, globally and in four major world regions under different carbon tax scenarios with and without the availability of CCS technologies.

reduction in carbon intensity per tonne clinker (Fig. 11). This causes a reduction in total global final energy use for cement production, even in the baseline scenario, although clinker production remains globally stable around 3000 Mt/yr.

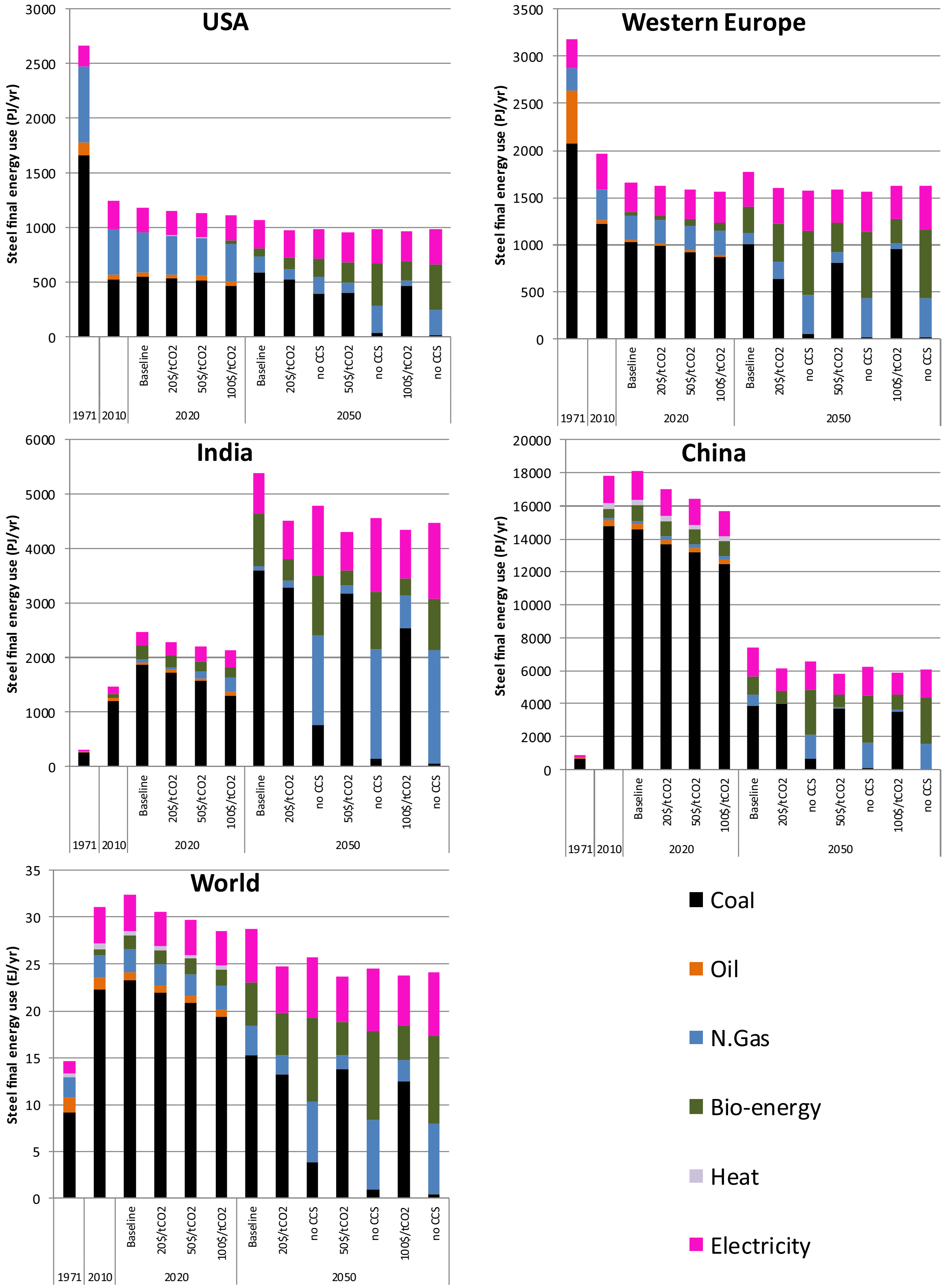

Fig. 6. Final energy use for steel production in four major world regions under different carbon tax scenarios.

Regarding energy use, it is important to note that cement ovens can be fed with many different fuels and historically cement ovens have been switching to use the cheapest available options. Globally, coal dominates the current fuel mix and is projected to increase its share. Historically the shares of fuels differed between regions, with a considerable share of natural gas in Western Europe and the USA, and coal dominating in India and China (Fig. 8). In the baseline scenario for 2020, fuel shares evolve along the same patterns as historic energy use in all these regions, even though there is considerable growth in final energy use in India and China. Towards 2050, the price of natural gas increases in the baseline scenario as result of depletion of cheaper resources. Therefore, the use of natural gas

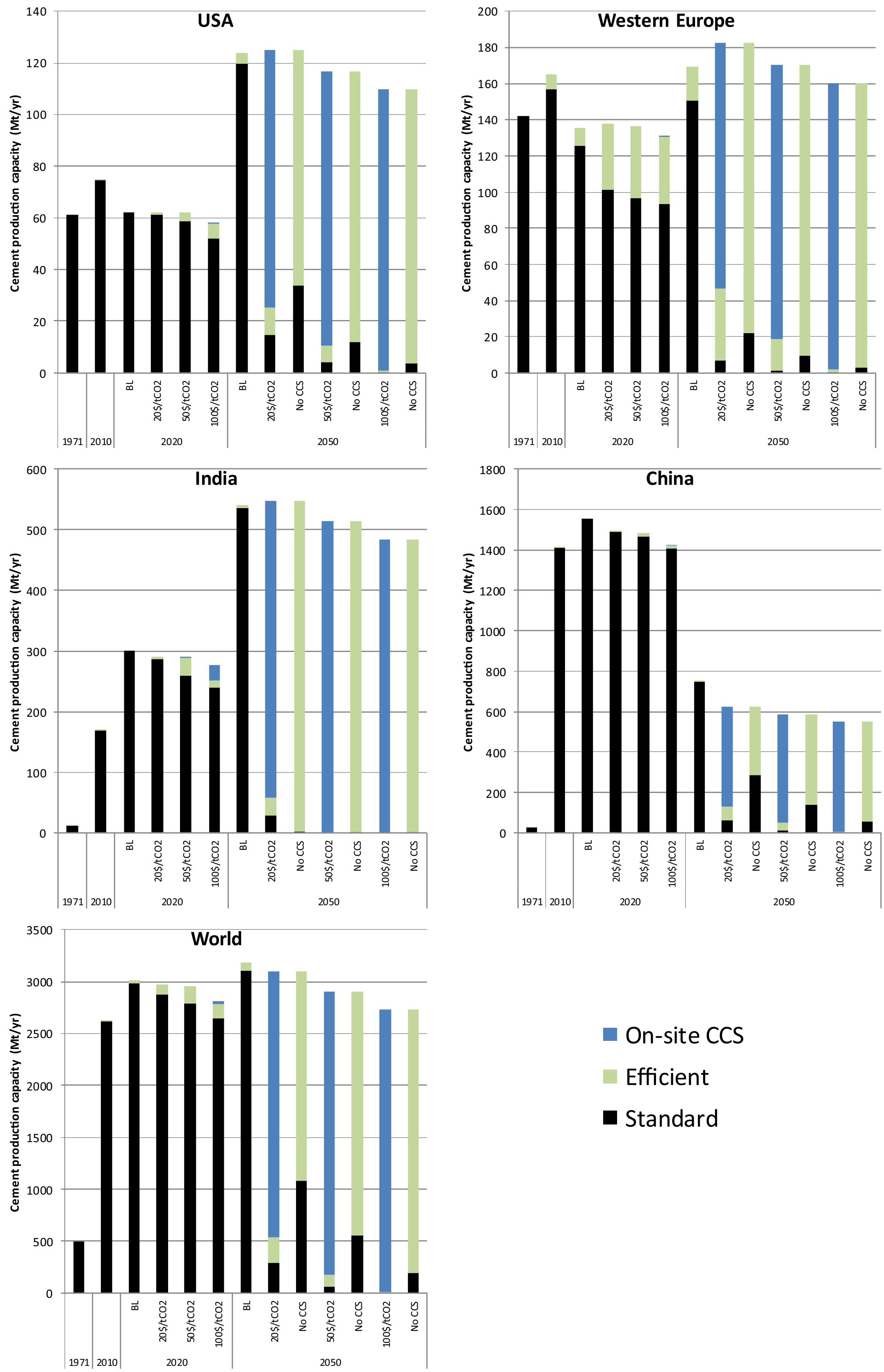

Fig. 7. Production of cement (clinker) from different technologies for the world (right panel) and four major world regions (left panel) under the OECD-EO baseline (BL) scenario and different carbon tax scenarios. Lower production capacity at higher carbon taxes is due to decreased demand through decreasing clinker ratios.

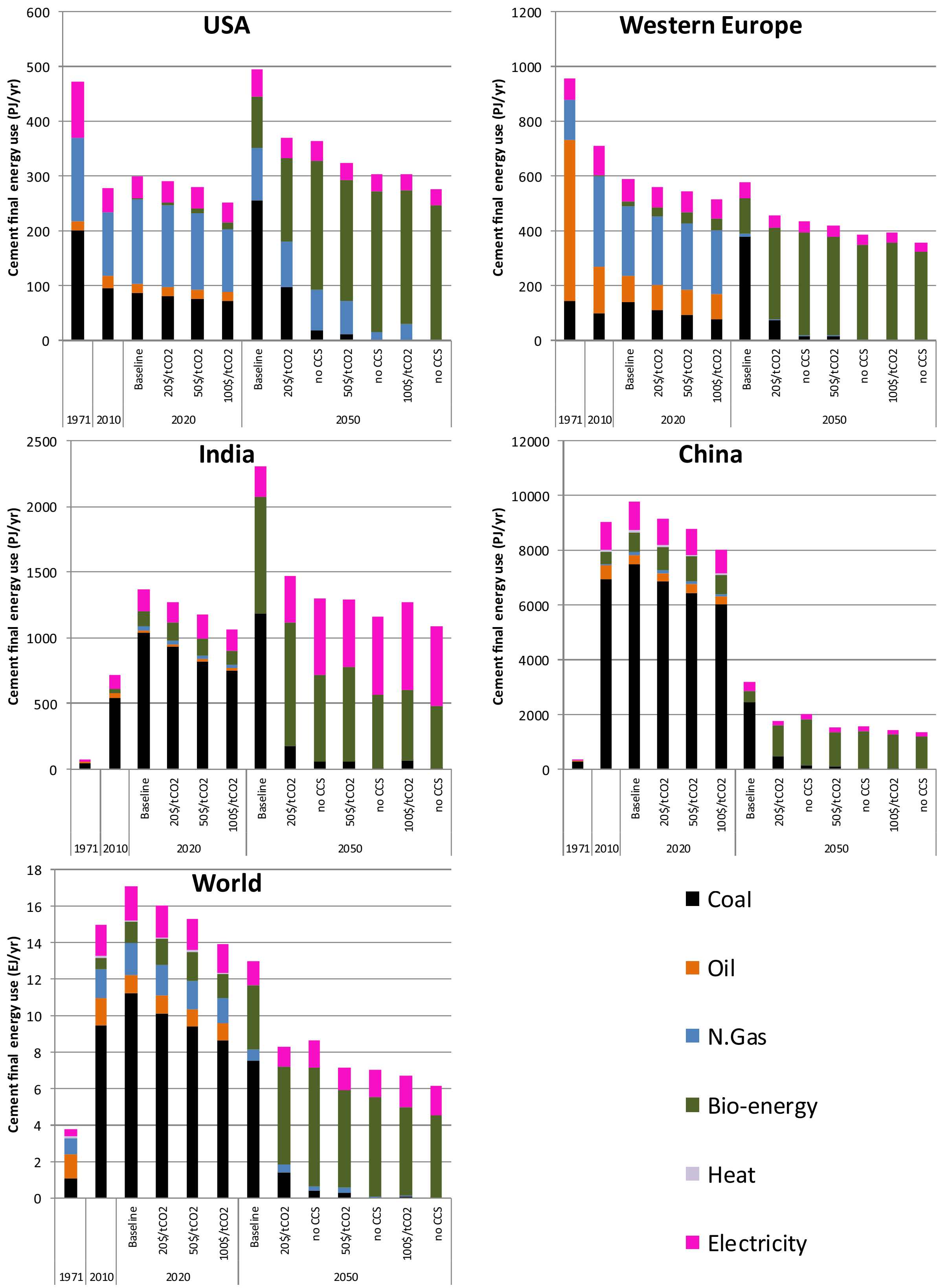

Fig. 8. Final energy use for cement (clinker) production in four major world regions under different carbon tax scenarios.

for cement production decreases in the USA and Western Europe, which are switching towards cheaper coal and bioenergy (including combustible waste). In India, bioenergy plays an increasing role in the baseline scenario as well. Globally, CO_2 emissions from the cement sector are projected to increase by 13% between 2010 and 2020, from 3050 to 3450 $MtCO_2$/yr after which they decline to about 2900 $MtCO_2$/yr by 2050. Emissions from energy use for cement production decrease slightly in the USA from 35 to 34 $MtCO_2$/yr and

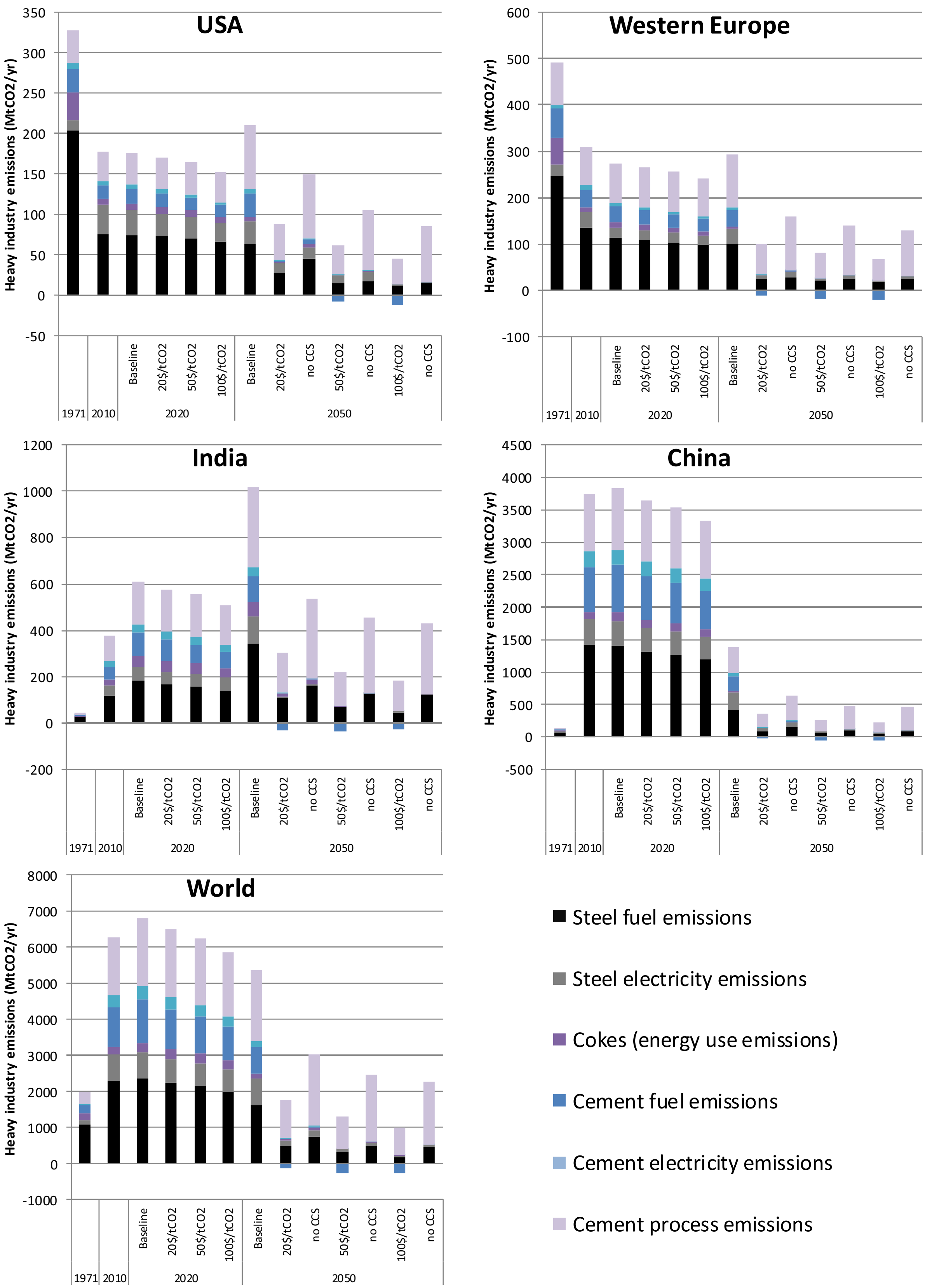

Fig. 9. CO_2 emissions from steel and cement production energy use, and cement process emissions under different carbon tax scenarios.

considerably in Western Europe from 87 to 55 $MtCO_2$/yr in 2050 (Fig. 9) as result of increased biofuel use. In China and India, the growth in demand and production leads to an increase of CO_2 emissions from energy use. The Chinese cement industry emitted a total of 1400 $MtCO_2$/yr (including process emissions) in 2010, which increases to about 1900 $MtCO_2$/yr in 2020, and decreases to about

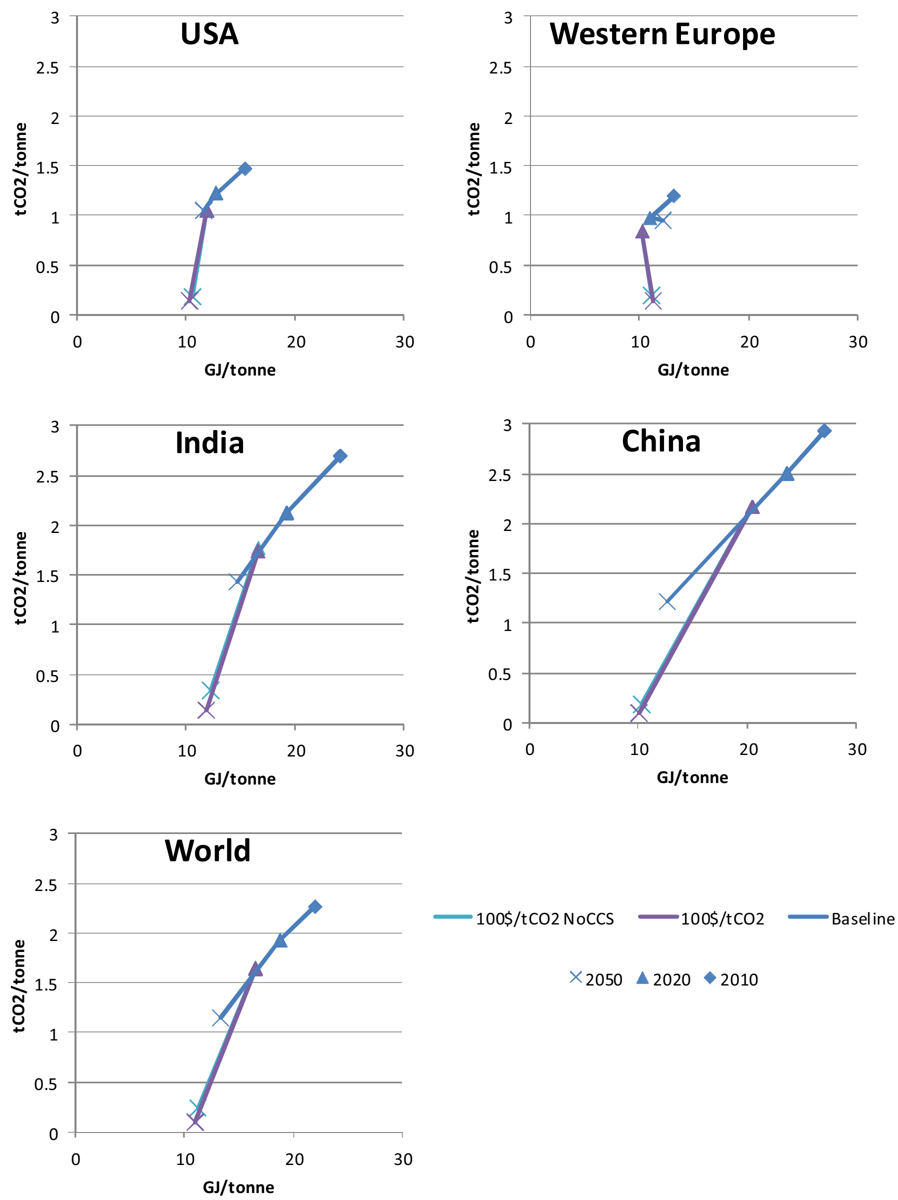

Fig. 10. Development of energy intensity and carbon intensity per tonne steel produced in several world regions in 2010, 2020 and 2050 at carbon tax levels of 100 $/tCO_2$ + 4%pa with and without CCS available. We only show the high carbon tax scenario to avoid too many overlapping lines and indicate the maximum range of change in our model.

630 $MtCO_2$/yr in 2050. Cement industry emissions in India increase steadily, from 145 $MtCO_2$/yr in 2010 to 320 and 470 $MtCO_2$/yr in respectively 2020 and 2050.

4.2. Mitigation scenarios

We analyze the mitigation potential by introducing a carbon tax in the model. Once a carbon tax is applied, carbon intensive production options become more expensive and choices for energy carriers and production technologies start to shift towards lower greenhouse gas emissions. Moreover, demand for clinker decreases due to changing mixing ratios for clinker in cement. We analyze carbon tax scenarios that start at 20, 50 and 100 $/$tCO_2$ in 2020 and increasing with 4% per year afterwards (Table 7). It is important to note these increasing values over time, since it changes to cost effectiveness of certain technologies over the course of the next decades. This pattern of increasing carbon tax values is common in recent model comparison and diagnostics studies (Calvin et al., 2012; Clarke et al., 2016; Kriegler et al., 2015). We analyze scenarios with and without the availability of carbon capture and sequestration, since the development of this technology is one of the main uncertainties in the future abatement potential of the steel and cement industries.

By 2050, with moderate climate policy (20 $/$tCO_2$ + 4$pa) COREX + CCS can be enabled in the steel sector whereas efficiency measures will be the dominating low-carbon technology in the short term. In the cement sector, production routes will be limited to the standard efficiency technologies, but in the long-term a similar carbon tax as for the steel sector can offer significant potential for GHG emission reduction mainly by CCS and to some extent by energy efficiency technologies.

In the iron and steel sector, higher carbon taxes by 2020 show a slight increase of primary EAF technology shares at the expense of efficient blast furnace technology. By 2050 with CCS available, the carbon tax scenarios show a mixture of COREX-CCS and EAF (with CCS) technologies. Without CCS available, steel production

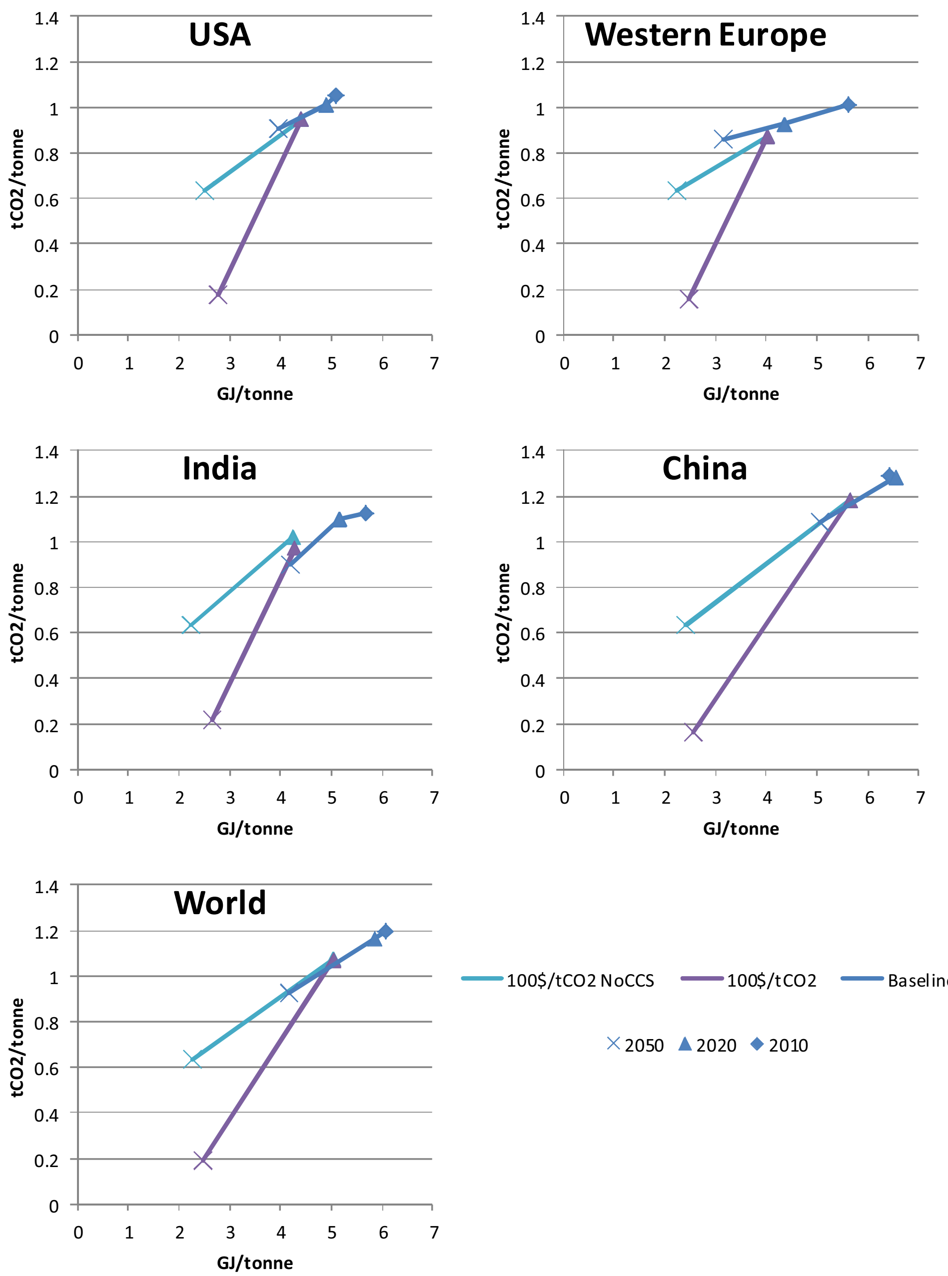

Fig. 11. Development of energy intensity and carbon intensity per tonne clinker produced in several world regions in 2010, 2020 and 2050 at carbon tax levels of 100 $/tCO_2$ + 4%pa with and without CCS available. We only show the high carbon tax scenario to avoid too many overlapping lines and indicate the maximum range of change in our model.

Table 7
values for carbon tax scenarios.

	20 $/tCO_2$ + 4%pa	50 $/tCO_2$ + 4%pa	100 $/tCO_2$ + 4%pa
2020	$20	$50	$100
2030	$30	$74	$148
2040	$44	$110	$219
2050	$65	$162	$324

changes almost completely to EAF in all regions (based on electricity that is almost fully decarbonized). In terms of energy intensity, the carbon tax scenarios lead to an increased reduction in energy per tonne steel, largely caused by the application of more efficient technologies and EAF (Fig. 10). The reduction in emission intensity is comparable with and without CCS, showing a stark decrease either driven by CCS in the steel sector itself or full decarbonization of the power sector (Fig. 10). In scenarios with CCS final energy use of the steel sector becomes dominated by coal, bioenergy and electricity. Without CCS, coal is phased out and replaced by electricity, natural gas and bioenergy. Total final energy use is reduced in carbon tax scenarios due to the application of more efficient technologies. Emissions of CO_2 are strongly reduced under the carbon tax scenarios: globally by 6–15% below baseline by 2020, 70–90%

below baseline by 2050 with CCS and 60–80% by 2050 without CCS, depending on carbon tax levels. The individual regions show a similar pattern and magnitude of emission reductions. Cokes production is completely phased out with the highest carbon taxes and the combination of electricity-based EAF and high carbon-capture rates, leads to deep emission reductions in most regions.

For the cement sector, the changes in 2020 are small, as the carbon taxes have just been introduced. Only the 100 $/tCO_2$ scenario shows a minor reduction in clinker production due to changed mixing-ratios. However, by 2050 cement production is dominated by more efficient plants or (if the scenario allows) on-site CCS in all regions (Fig. 7). For cement, the availability of CCS makes a larger difference in carbon intensity than for steel, as cement has fewer options to benefit from decarbonization in the power sector in scenarios without CCS. However, the shift to more efficient technologies causes a major reduction in energy intensity of clinker production (Fig. 11). Final energy use changes in the carbon tax scenarios with a clear decrease in coal with higher carbon taxes and an increase in the use of electricity and bioenergy (Fig. 8). Total final energy use decreases, due to the application of more efficient technologies, but also due to reduction of total clinker production as result of lower mixing ratios. Consequently, emissions decrease as well. Globally by 4–13% below baseline in 2020 and 30–40% in 2050 without CCS and 70–80% below baseline by 2050 with CCS, depending on the level of carbon tax (Fig. 9). Emission reductions from cement production in the major world regions are of the same magnitude, ranging from about 30% below baseline in 2050 without CCS under 20$/tCO_2$ + 4%pa carbon tax up to about 80% under a carbon tax of 100 $/tCO_2$ + 4%pa with CCS.

4.3. Comparison to existing literature

We compare the global results for the steel and cement sectors with several major studies in the literature. We focus here mostly on aggregated trends in total material production, final energy use and CO_2 emissions. Detailed comparisons are complicated by differences in assumptions on population and economic growth, technology development, technology availability assumption and definitions of carbon taxes.

With respect to global steel production and consumption, our projections seem on the high side of the literature range for 2030, but below the existing projections for 2050 (Fig. 12). The latter is caused by the stabilizing pattern that we have found for per capita steel consumption in combination with the assumed increase in material efficiency of 1% per year which reduces steel intensity on the longer term. Interestingly, it should also be noted that the IEA ETP (IEA, 2012, 2015) projections have come down between the 2012 and 2015 editions from almost 3000 Mt by 2050 to about 2200 Mt steel and they could well take similar positions as our projections in further updates given current Chinese trends.

With respect to final energy use (Fig. 12), our projections are well below the IEA (2009) baseline projections for 2050, but also here, the ETP projections have come down over time and the (IEA, 2015) scenarios are only slightly above our projections. The technology mix can have considerable impact on the total final energy use. For instance, EAF is more efficient than BOF and leads to lower final energy use and CCS technology has an efficiency-decreasing impact on final energy use, leading to higher energy use, but deeper emission reductions. CO_2 emissions in our study are lower than the existing literature, both for the baseline and in mitigation scenarios. For the baseline, the increased role of bioenergy in our SSP2 scenario might play a role. For mitigation scenarios, differences originate from different system boundaries, the availability of CCS and the definition of carbon taxes. Due to the integration of this model within a global energy model, carbon taxes lead to a shift in steel production towards EAF which benefits from decarbonization of the power sector. Studies that look only into the steel sector do not have such benefit. In our study, carbon taxes increase by 4% per year after 2020, whereas other studies use constant carbon taxes (Akashi et al., 2011) or aim for a specific target without analyzing the costs (Allwood et al., 2010; IEA, 2015; Milford et al., 2013). In general, our high carbon tax scenarios are well below the range of 450 ppm scenarios as presented in the IPCC AR5 (Fischedick et al., 2014), suggesting that lower carbon taxes will already lead to such stabilization scenarios.

Fewer studies exist that describe scenarios for the cement sector (Fig. 13). However, the available results from the literature indicate that our projections for total global cement demand (comparing Mt Cement per year, not just clinker) are in line with the literature. Final energy projections of our baseline scenario are roughly in line with IEA (2009) and (IEA, 2015) projections for 2050. However, with high carbon taxes final energy use drops stronger in our model than in the ETP, largely driven by substituting clinker for other materials. Baseline emissions are a little higher than existing literature, but our model shows larger potentials for emission reduction, especially in scenarios with CCS technology available. CCS is not considered in the IEA ETP scenarios, but our results are in line with the numbers presented in the IPCC AR5 (Fischedick et al., 2014). Without CCS, emission reductions are more in line with the existing literature that does not consider CCS technology. A large portion of the emission reduction with CCS is due to the application of bioenergy with CCS and it is worth noting that such technology is not yet applicable and it is unclear what the potentials are for this technology in the cement industry.

5. Discussion

The model presented in this paper fills a gap in the existing literature as a relatively detailed bottom–up steel and cement model embedded in a long-term global energy system model. Although models exist that focus on industrial subsectors in specific regions (Wen et al., 2015; Wen et al., 2014; Zhou et al., 2013), this is a first global study of such model. Our model also includes a higher level of technology detail than other integrated assessment models.

The main uncertainties in this model are related to the simulation of demand for materials, and the dynamics of the production model. With respect to the first, we approximate the demand for steel and cement as a function of GDP per capita, relating a certain income level to a certain demand for material. Moreover, regions that historically deviate from this generic relation converge (albeit slowly) towards a global average curve, staying below or above the global average for the next decades. Others have argued that the cumulative use of steel and cement per capita would be a better representation of simulating the relation between economic development and material demand, especially since steel and cement represent the buildup of essential infrastructures. Moreover, extrapolating historical relations between economic activity and material consumption towards future is inherently uncertain, since it, for instance, overlooks the possibility of changes in material consumption patterns and radical substitution of steel and cement by less (or more) energy intensive materials.

One option for uncertainty analysis in our model is the implementation of different scenarios. We have implemented the projections for GDP and population for SSP1 (Sustainability: high economic growth, low population growth, material extensive consumption) and SSP3 (Regional Rivalry, low economic growth, high population growth, material intensive consumption) (Chateau et al., 2015; Samir and Lutz, 2015; O'Neill et al., 2015) to estimate ranges of future consumption under these circumstances (Fig. 14). The total global consumption of steel turns out to be rather constant between these scenarios, but with differences between regions. For

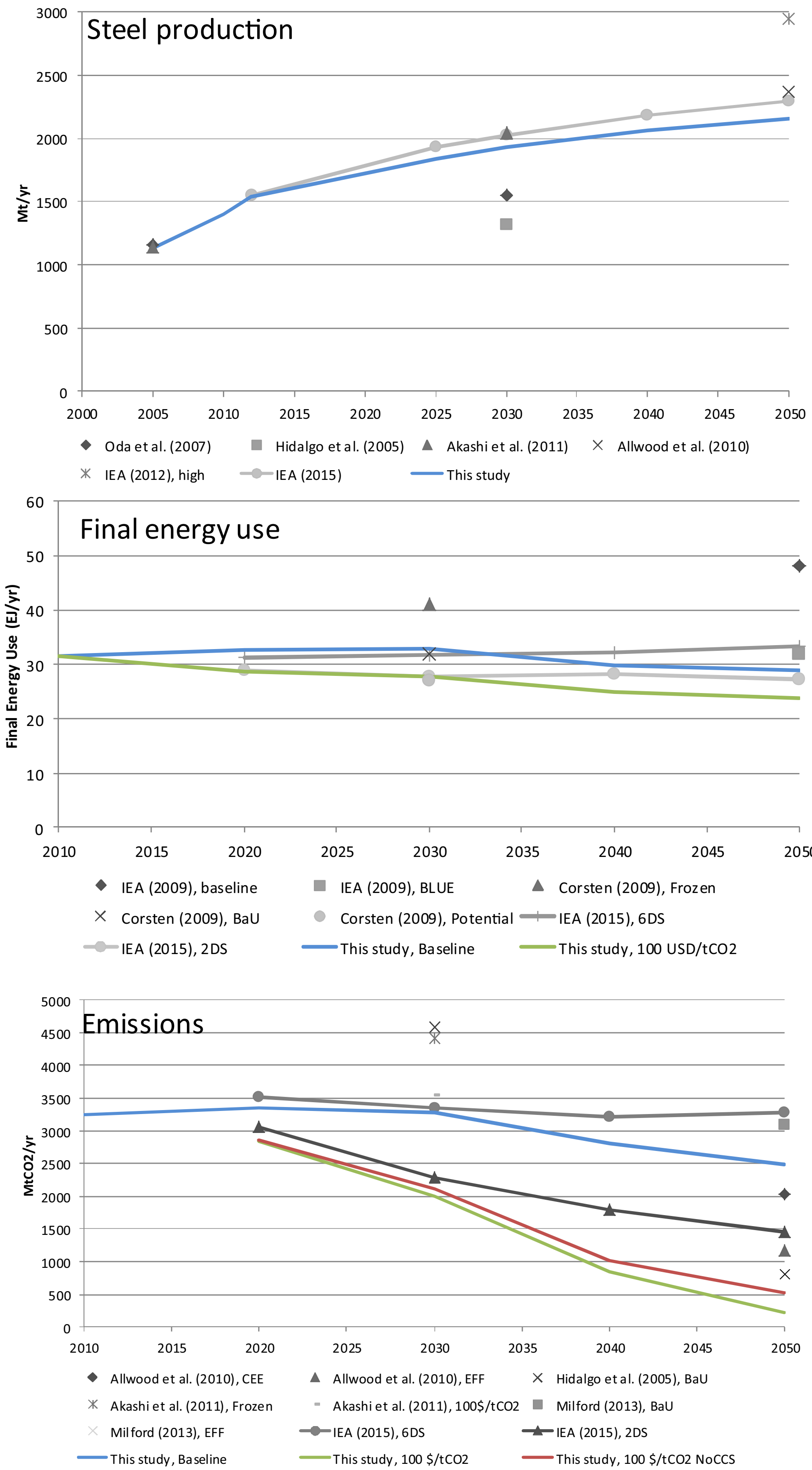

Fig. 12. Comparison of global steel production, final energy use and CO_2 emissions for this study and major other studies in literature.

instance, consumption in China is more dominant under SSP3 than SSP1. For countries with higher GDP per capita and more saturated demand, the difference in lifestyle dominates the scenarios (see Fig. 14 lower panel USA, Europe and China). However, for developing countries the difference in GDP per capita is more decisive and lower growth in SSP3 leads to lower steel consumption (see

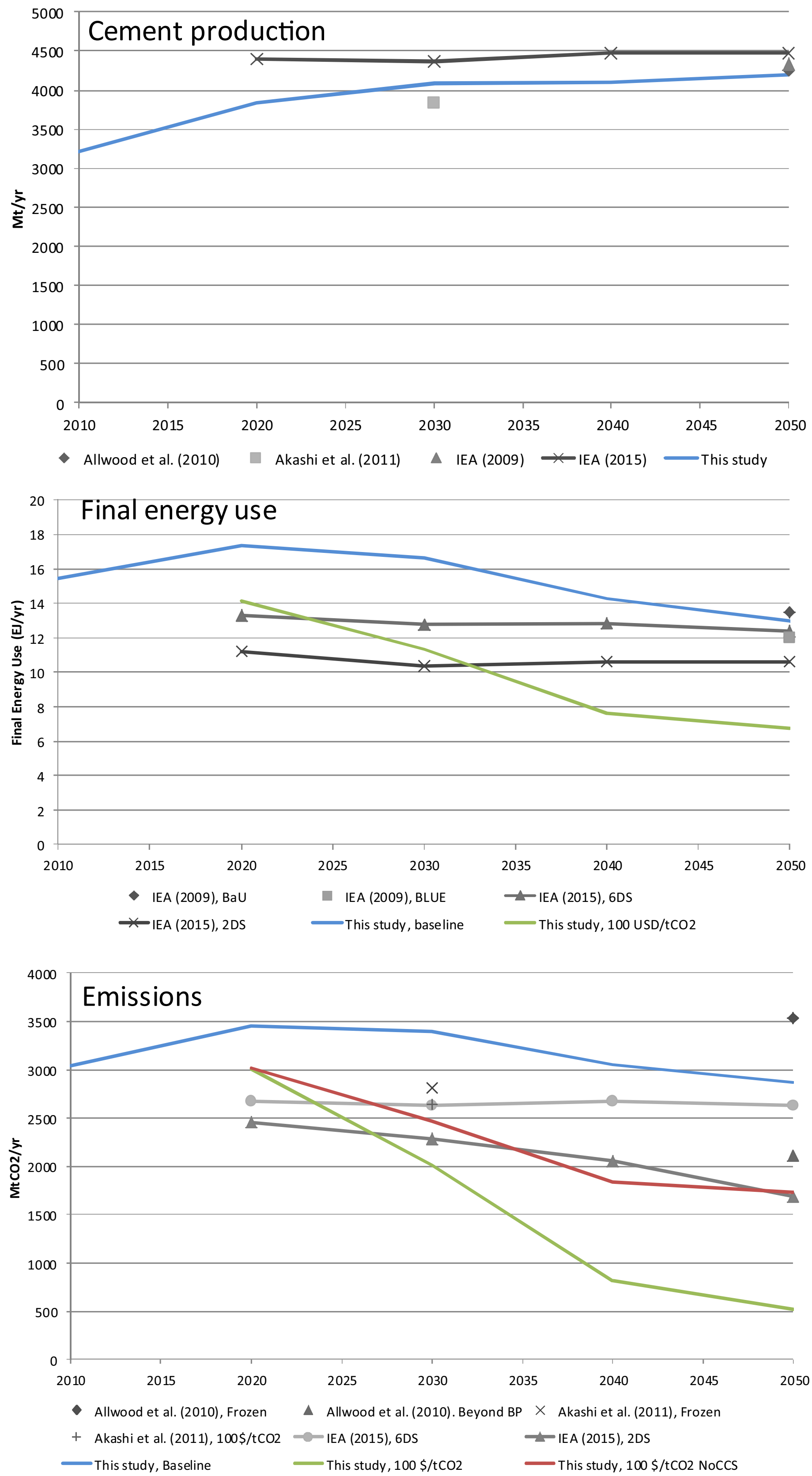

Fig. 13. Comparison of global cement production, final energy use and CO_2 emissions (incl. process emissions) for this study and major other studies in literature.

India in Fig. 14 lower panel). The latter effect appears to dominate the global per capita projections in these scenarios. For cement, the income effect is weaker, as demand is projected to increase stronger at lower income levels. Therefore, the differences in assumptions on material intensity of consumption dominate in these scenarios,

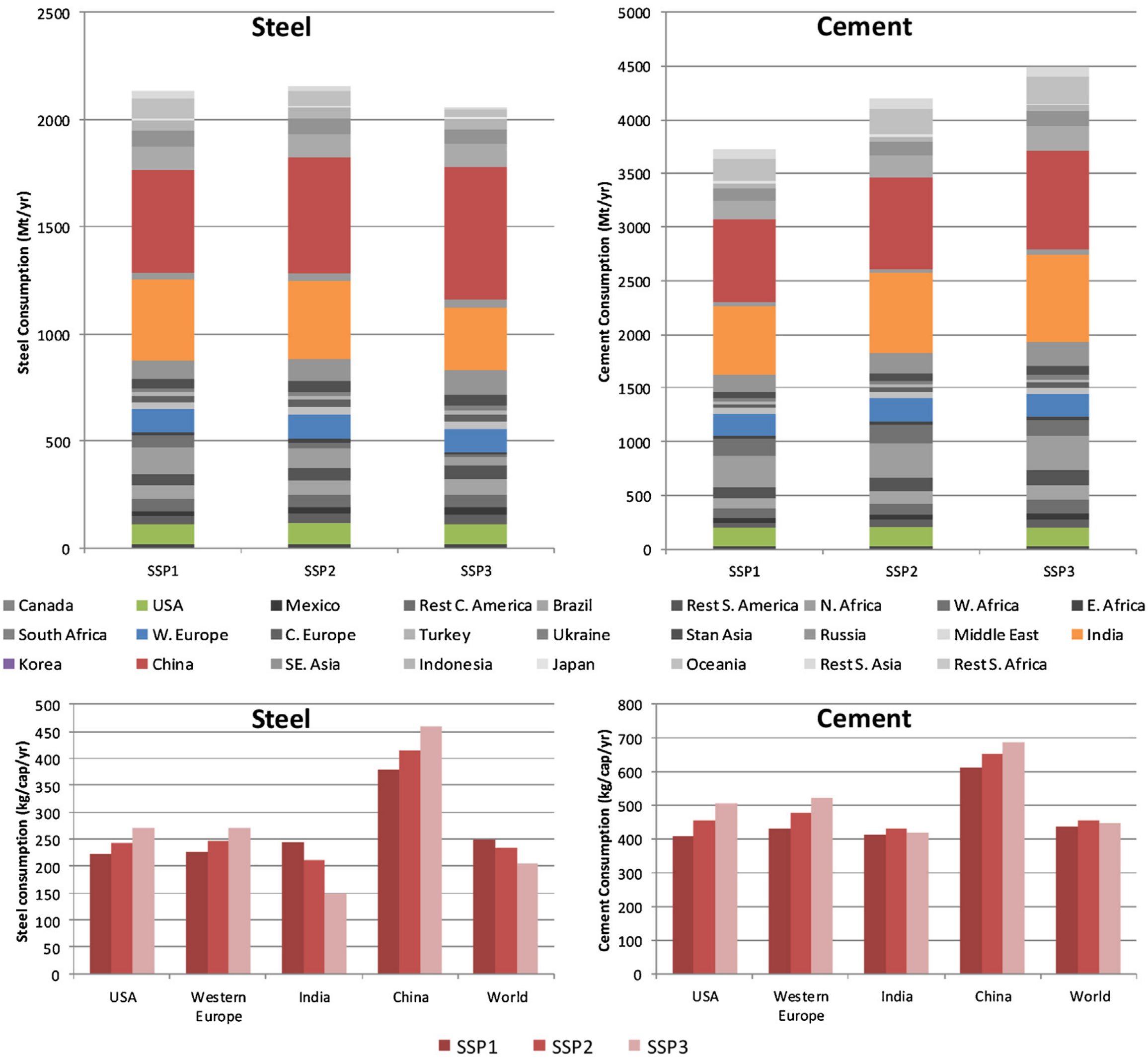

Fig. 14. Projections for total (top) and per capita (bottom) steel and cement consumption under different SSPs in 2050.

leading to higher per capita and total consumption levels in SSP3 compared to SSP1.

With respect to the dynamics of the material production major uncertain elements include trade, stock turnover, retrofitting, technology assumptions and other technologies. The assumed approach to trade is to allow for a shift in production between regions, but only slowly, if cost differences between regions deviate considerably and assuming that only a minor share of steel and cement will be traded in the future as well. In the model it is assumed that production plants have to fulfill the full economic lifetime of 40 years. As no retrofitting is explicitly incorporated in our model changes in technologies and emission reductions evolve slowly in our scenarios. Hence, our results might underestimate the emission reduction potential, especially for the short-term. Finally, only major technology options have been included in this model, which cover the range of available technologies for steel and cement production in terms of costs, energy use and emissions.

6. Conclusion

In this paper, we present a model for the steel and cement industry that is calibrated to key historical trends with respect to patterns of steel and cement consumption and choices between production technologies.

This model can be used to make future projections and estimate future energy use, CO_2 emissions, and emission reductions in the steel and cement industries. The model has been calibrated against historical trends for different global regions using data for consumption, production and energy use.

Without climate policy, the future projections based on the SSP2 scenario show a rapid increase in the consumption of steel and cement over the next few decades, after which demand levels are projected to stabilize. This implies that over the scenario period, CO_2 emissions are projected to peak in the next decades followed by a decrease below 2010 levels in 2050. Steel consumption increases from present day 1537 in 2010 to 2160 Mt/yr by 2050, and cement grows from present day 3220 Mt/yr to 4200 Mt/yr in 2050. In steel production, the increasing availability of scrap dominates technology choices in developing countries. For both steel and cement, the baseline scenario described a reduction in energy intensity and carbon intensity due to more efficiency technologies and the increased use of bioenergy and natural gasIn the baseline, CO_2 emissions for steel production are projected to go from 3250 $MtCO_2$/yr in 2010 to 3350 MtCO2/yr in 2020, after which they decrease slowly to 2500 MtCO2/yr in 2050. For cement, baseline emissions increase by 13% between 2010 and 2020, from 3050 to 3450 $MtCO_2$/yr after which they decline to about 2900 $MtCO_2$/yr by 2050.

There is considerable scope to mitigate CO_2 emissions from steel and cement industries, leading to resp. 80–90% and 40–80% reduction below 2010 in 2050 for a carbon tax of 100 \$/tCO_2 + 4%pa depending on the availability of CCS. Such reductions are higher than those required for a 2° climate change scenario. Under carbon tax scenarios between 20 and 100 \$/tCO_2 and increasing with 4% per year global CO_2 emissions from the steel sector can be reduced by 6–15% below baseline (3–12% below 2010) by 2020, 70–90% below baseline (80–93% below 2010) by 2050 with CCS and 60–80% (70–84% below 2010) by 2050 without CCS. Under the baseline scenario, the production of cement shifts slowly towards more efficient technology, a trend that is increased in carbon tax scenarios, in which also CCS technology also plays a role. Under carbon tax scenarios between 20 and 100 \$/tCO_2 and increasing with 4% per year, global CO_2 emissions from the cement sector can be reduced by 4–13% below baseline (+9 to −1% compared to 2010) in 2020 and 30–40% (30–40% below 2010) in 2050 without CCS and 70–80% below baseline (70–80% below 2010) by 2050 with CCS.

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orrigendum

orrigendum to "Long-term model-based projections of energy use and CO_2 missions from the global steel and cement industries" [Resour. Conserv. ecycl. 112 (2016) 15–36]

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The authors regret that, as a reader informed us, the presented istoric data for steel production from scrap did not match the available ata sources for the USA and Western Europe. A close inspection of the odel code revealed that for the historic period 1971–2010, the market hare for scrap was erroneously allocated twice (once forced by the crap availability and a second time as part of the historic data on roduction shares). As a result, our model indicated a too high production share of steel from scrap in the year 2010, which also influenced the results for 2020 due to slow turnover of the production stock. he results for 2050 were not influenced by this error because there is a ull capital stock turnover between 2010 and 2050. Since this error only nfluenced the market allocation of steel production technologies, and ot the total level of steel production, correcting this error only lead to inor changes in the composition of final energy use and CO_2 emisions. The regions with the largest adjustments are those with high hares of steel recycling, such as Western Europe and the USA.

We have corrected this error, reran all scenarios with the updated odel, and present below a corrected version of the text and figures hat were influenced by this error.

The main changes are related to Section 4.1.1 in the original paper. nstead of electric arc furnace (EAF) accounting for 75% and 66% of teel production in 2010 in respectively the USA and Western Europe, his now only represents around 50% and 42%. Future projections for AF to account for 60% and 50% by 2050 are similar, but indicate an ncrease of scrap share rather than a decrease (as mentioned in the original paper). For India and China the share of EAF in total steel production now increases respectively from 10% to 30% and 10% to 50% between 2010 and 2050 (originally the 2010 values were 13% and 18%, respectively). Globally, the share of scrap-EAF increases from 23% in 2010 to over 40% by 2050 (instead of remaining stable around 40% in the entire period).

There are only minor changes in the results for energy intensity per tonne steel, carbon intensity per tonne steel and final energy for steel production. These changes do not influence any trends and numbers discussed in the text, but we have included the updated figures in this addendum.

The emissions of carbon dioxide (CO_2) from steel production have changed slightly as result of correcting the error with scrap EAF. Global CO_2 emissions are now 3215 megatonnes (Mt) CO_2 per year (yr) in 2010 (was 3250 $MtCO_2$/yr) and 3525 $MtCO_2$/yr by 2020 (was 3350 $MtCO_2$/yr) but remain around 2500 $MtCO_2$/yr in 2050. Emissions in the USA and Western Europe are still decreasing from 110 Mt (was 150 Mt) to around 100 $MtCO_2$/yr by 2050 and from 170 Mt (was 180 Mt)[1] to around 140 $MtCO_2$/yr, respectively. Chinese emissions still peak and decline, but start from a higher level at present-day and near future. Steel production emissions in China are now 1940 (was 1660 Mt) $MtCO_2$/yr in 2010 and develop to 2030 $MtCO_2$/yr (was 1920) in 2020 and 700 $MtCO_2$/yr in 2050. Changes for India are negligible. Only its 2010 emissions increased to 185 (was 160 Mt) $MtCO_2$/yr.

Below are the revised figures that were influenced by correcting the error. Figure numbers refer to those in the original paper.

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[1] The original text contained a typo for European CO_2 emissions in 2010, it stated 300 Mt instead of 180 Mt.

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Apart from this discussed error in the model, we found one typo in he paper. In Table 4, the Specific Energy Consumption (SEC) in 2010 GJ/tonne) for Coal BF + BOF should be 25.5 and not 20.4. This was orrect in the model itself, but a typo in the paper.

The authors would like to apologise for any inconvenience caused.

Fig. 1 Production of steel, globally and in four major world regions under different carbon tax scenarios with and without the availability of CCS technologies.

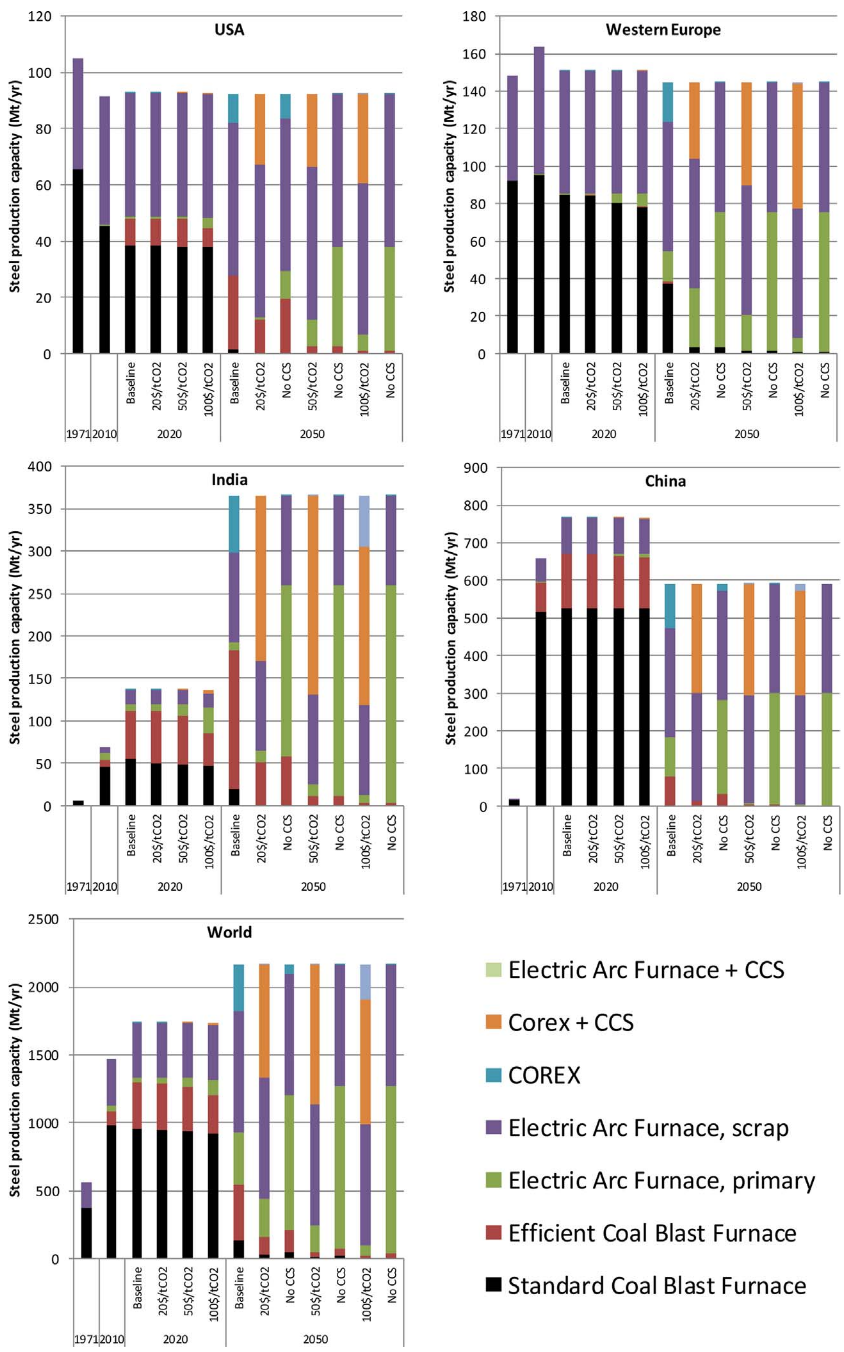

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Fig. 2 Final energy use for steel production in four major world regions under different carbon tax scenarios

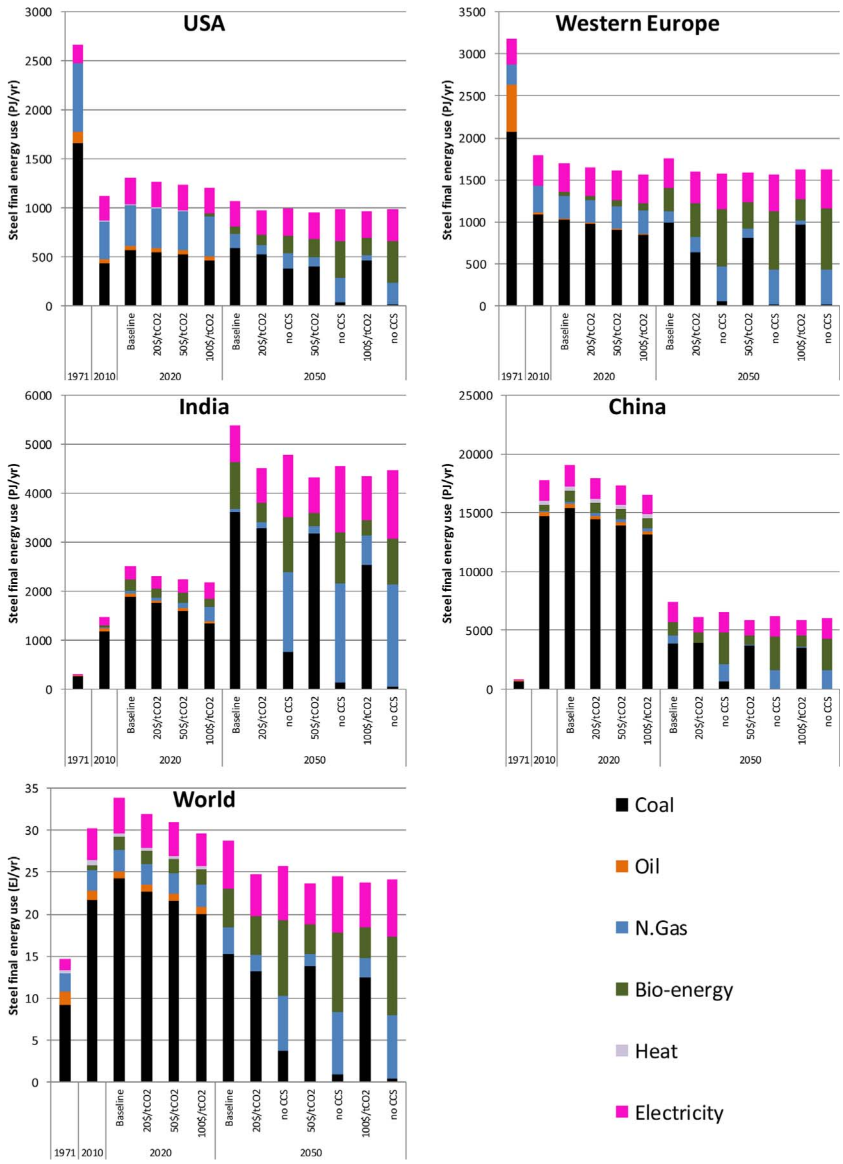

Fig. 3 CO_2 emissions from steel and cement production energy use, and cement process emissions under different carbon tax scenarios.

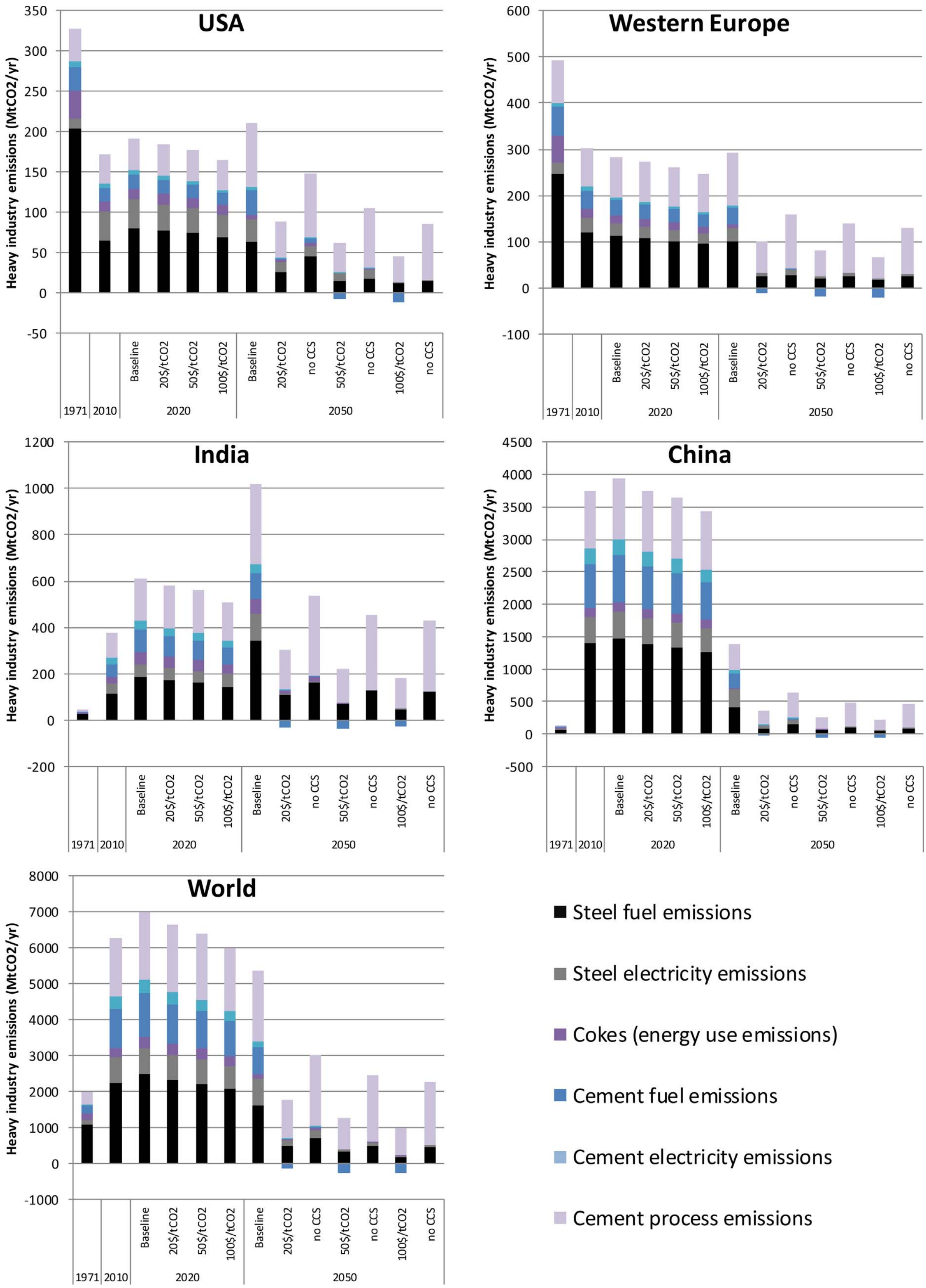

Fig. 4 Development of energy intensity and carbon intensity per onne steel produced in several world regions in 2010, 2020 and 2050 t carbon tax levels of 100 $/tCO2 + 4%pa with and without CCS available. We only show the high carbon tax scenario to avoid too many overlapping lines and indicate the maximum range of change in our model.

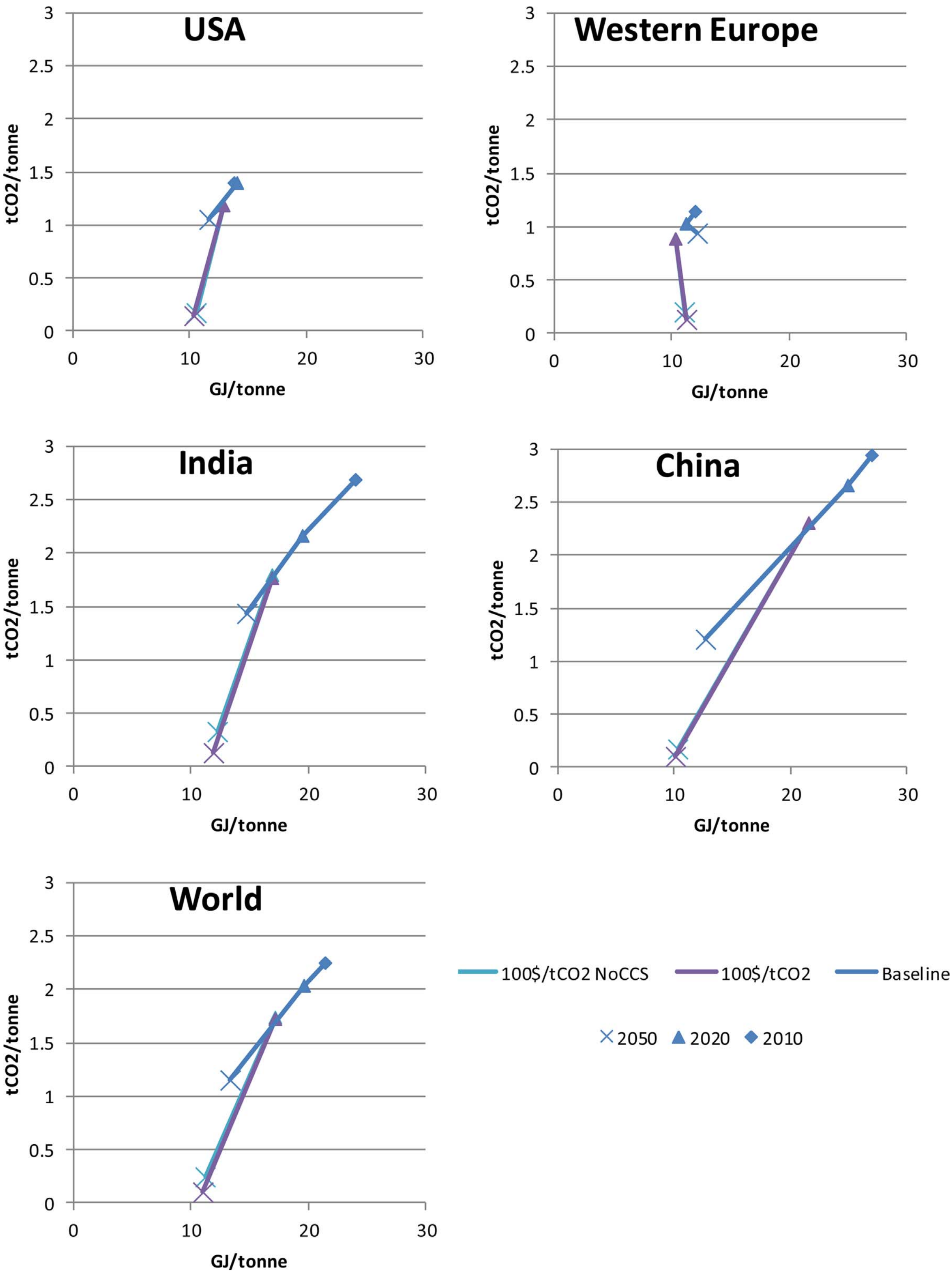

Fig. 5 Comparison of global steel production, final energy use and CO_2 emissions for this study and major other studies in literature.