



Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models



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ABSTRACT

The industry sector is a major energy consumer and GHG emitter. Effective climate change mitigation strategies will require a significant reduction of industrial emissions. To better understand the variations in the projected industrial pathways for both baseline and mitigation scenarios, we compare key input and structure assumptions used in energy-models in relation to the modeled sectors' mitigation potential. It is shown that although all models show in the short term similar trends in a baseline scenario, where industrial energy demand increases steadily, after 2050 energy demand spans a wide range across the models (between 203 and 451 EJ/yr). In Non-OECD countries, the sectors energy intensity is projected to decline relatively rapidly but in the 2010–2050 period this is offset by economic growth.

The ability to switch to alternative fuels to mitigate GHG emissions differs across models with technologically detailed models being less flexible in switching from fossil fuels to electricity. This highlights the importance of understanding economy-wide mitigation responses and costs and is therefore an area for improvements. By looking at the cement sector in more detail, we show that analyzing each industrial sub-sector separately can improve the interpretation and accuracy of outcomes, and provide insights in the feasibility of GHG abatement.

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1. Introduction

In 2010, the industry sector was responsible for 37% of total global final energy consumption and emitted more greenhouse gas (GHG) emissions than any other sector¹ [1,2]. While energy intensity of the industry sector mostly decreased in recent years (due

to the adoption of energy and material efficiency measures), total energy use still increased as a result of production growth and a shift towards more energy intensive industrial products [3]. The International Energy Agency (IEA) projects that industrial energy use would continue to increase, approximately doubling in 2050 compared to the consumption of 126 EJ² in 2009, under the assumption of a continuation of current trends. This would lead to an increase of industrial CO₂ emissions by 45–65% [4]. Effective climate policy would therefore require steep emission reductions in the industry sector to reach stringent climate targets [2].

Energy-economy models and Integrated Assessment Models

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¹ The total energy demand is usually broken down into four end-use sectors: industry, transport, buildings and agriculture, forestry and other land use (AFOLU).

² This figure includes energy use as a feedstock, energy use in blast furnaces and coke ovens (own energy use and transformation energy) and excludes energy use in refineries.

(IAMs) are frequently used to analyze emission reduction strategies and associated investment costs. The models are able to provide a consistent picture of the global energy system and analyze trade-offs and synergies in mitigation actions across different sectors [5].

Traditionally, end-use sectors such as the industry sector are represented in most models in a rather stylized manner. More recently, however, several models have started to include more sector details. This does represent a challenge as, compared to supply sectors, end-use sectors are highly diverse and use a large variety of different technologies [6]. Also in the industrial sector energy consumption is driven by many different industrial processes to manufacture a wide variety of products³ [7,8].

The IPCC Fifth Assessment report shows that current scenarios display a wide range of industry sector emissions for the 21st century, but provides little analysis of the underlying reasons for these differences [5]. Still, to design effective mitigation policies, a better understanding of possible future emissions and the reason for model differences is needed [9]. Over the last few years, many model comparison studies have been published which looked at the behavior of IAMs. A few studies focussed on the energy and land-use systems as a whole, such as comparing technology diffusion [10], the role of low carbon technologies for energy transformation [11]; regional projections [12]; and exploring mitigation costs [13]. Some studies have also looked at specific sectors or technologies such as the transport sector [14] or specific forms of renewable energy such as bio-energy [15]. However, at the moment, hardly any study has looked into the industrial end-use sector. In addition to the limited comparison in the IPCC Assessment Report, studies have mostly looked into the representations of different models for specific regions such as China [16] or sectors such as the cement sector [17]. In this study therefore, we present a first detailed comparison of the industrial sector representation within IAMs and other energy-economy models, discussing model outcomes but also model assumptions to better understand the differences in model behavior. In addition, we take a detailed look into one major industrial sub-sector - the cement industry - in terms of global energy consumption to assess the more detailed sub-sector representation of a selection of models.

The article is structured as follows. In Section 2, we present the methods used in this study. In Section 3, we provide an overview of the industry sector representation in models and in Section 4, model projections for the industry sector of different models are presented for a “baseline scenario” (current trends) and a stringent mitigation scenario (“450 ppm scenario”). Next, in Section 5, specific attention is given to the modeling of the cement industry. Finally, in Section 6 the main results are discussed and the most important conclusions are drawn.

2. Method

The model comparison in this paper includes both IAMs and energy system models; we refer to the combination as long-term energy models. To better understand how the industrial sector is modeled, a questionnaire was sent to a set of long-term energy models included in the EU-FP7 ADVANCE project⁴ (AIM-CGE, DNE-21+, GCAM, Imaclim-R, IMAGE, MESSAGE, POLES, and TIAM-UCL). This questionnaire addressed model structure, system

boundaries, energy and material demand drivers, technology change and policy measures. The questionnaire results are discussed in Section 3. A more detailed model description of how the industrial sector is modeled is available in the [Supplementary Material](#).

2.1. Scenario description

For the detailed comparison of the industrial sector projections, outputs of *two scenarios* were collected:

- one scenario without new climate policies (“baseline scenario”) and,
- one scenario aiming at a stabilization level at 450 ppm CO₂-eq (“mitigation scenario”).

The model output was either generated specifically for this study or taken from earlier published results by these models as part of an Energy Modeling Forum study [11]. The modeling teams were asked to provide results for a medium-growth baseline, but there was no attempt to harmonize assumptions – thus taking different demographic and economy growth rates as part of the overall uncertainty (see Section 3.2). The study also included the *current policy scenario* of the IEA’s World Energy Outlook (WEO), that takes into account those policies and measures affecting energy markets that were formally enacted as of mid-2013, as well as the WEO 450 *scenario*, which stabilizes at around 450 ppm CO₂-eq in 2100 [18].

The model assumptions for global population and GDP are depicted in Fig. 1. These drivers stay relatively close across the range of models and to the WEO scenario in the coming decades, but start to diverge after 2035. In the 2011–2035 period, the WEO scenario shows an increase in global GDP (expressed in real purchasing power parity [PPP] terms) at an average annual rate of 3.6%. Population grows from 7.0 billion in 2011 to 8.5 billion in 2035 [18]. By the end of the century, there is a considerable difference in population projections with IMACIM-R and POLES showing a further increase in global population after 2070 – while all models show a peak followed by a decline in global population.

3. Description of the industry sector in global energy system models

3.1. Model characteristics

The eight models that participated in this study are widely used in IPCC assessment reports. Table 1 provides their general characteristics.

Although the distinction is not always clear, energy models are commonly categorized based on their disaggregation level into top-down and bottom-up models. Bottom-up models have a relatively high amount of technological detail. Most of the ‘bottom-up’ models are energy-system models focusing on the behavior of the energy system. Top-down models have less technological details and model the economy by taking into account interactions between the various sectors (e.g. the interaction between the energy sector and the rest of the economy). Most top-down models are so-called Computable Generic Equilibrium (CGE) models, representing the sectoral economic activities by production functions [19]. Another key difference across the models is the solution type used. This study includes intertemporal optimization models, in which an algorithm is used to optimize a distinct target across a period of

³ In this paper the term industry is used for all activities contributing to the production of goods and construction of building and infrastructure. Main industrial products are iron & steel, non-metallic minerals, chemicals & petrochemicals, pulp & paper, non-ferrous metals and other products.

⁴ All models presented here are part of the European Union Seventh Framework Programme FP7/2007–2013 ADVANCE project.

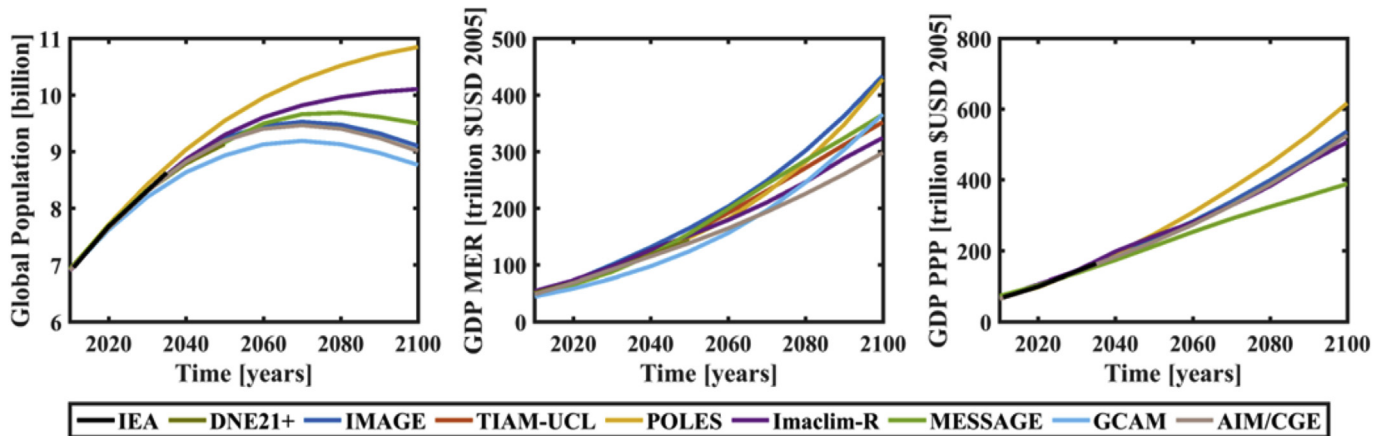


Fig. 1. Scenario drivers: a) Global Population; b) GDP expressed in Market Exchange Rates; c) GDP expressed in real purchasing power terms.

Table 1
General characteristics of the models studied.

	AIM-CGE	DNE-21+	GCAM	Imaclin-R	IMAGE	MESSAGE	POLES	TIAM-UCL
Type of model	CGE	Energy system model	Hybrid/IAM	Hybrid CGE framework with sectoral bottom-up modules	Hybrid/IAM	IAM based on bottom-up energy model	Energy system model	IAM based on bottom-up energy model
Solution type	Simulation	Intertemporal Optimization	Simulation	Simulation	Simulation	Intertemporal Optimization	Simulation	Intertemporal Optimization
Number of regions	17	54	14	12	24	11	57	16

time, as well as simulation models, that run based on a set of rules that determine the decisions made in every single time-period based on the information from the previous time step.⁵ The diverse set of models included in this study give a good representation of the broad range of type of long-term energy models.

3.2. Industry sector model characteristics

A key difference in industry modeling can be found in how the industrial sub-sectors are represented, i.e. the (explicit) representation of material demand, the model drivers, the technologies included and the assumptions regarding energy efficiency as described in Table 2.⁶

Economic and demographic drivers are either directly related to industrial energy demand or to the demand for materials and industrial products. The latter options allows for an explicit representation of various material production technologies and material recycling opportunities [2,20]. In CGE models, the projection of economic activity is the outcome of the production function, and energy intensity or material intensity improvements are typically represented by the substitution between capital, material, labor and energy inputs.

Some models include a detailed set of current and future technologies, characterized by their costs and efficiency. Technology deployment is modeled on the basis of relative costs, leading to

more efficient technologies deployed when fuel prices increase. Other models do not account for technologies explicitly, but technology development is driven by either exogenous assumptions or for example learning-by-doing based functions.

Finally, an important difference in modeling is the system boundary assumptions. Key differences among models are the inclusion or not of the energy use for feedstock purposes (also known as non-energy use of fuels) and the energy use in coke ovens and blast furnaces in the iron and steel industry. The energy use in refineries, agriculture and forestry are not included in the reported models industry data.

4. Global industrial model projections

4.1. Baseline scenario projections

4.1.1. Final energy demand

The baseline industrial final energy demand projected by each model (with and without feedstock use), is shown in Fig. 2. In the short-term (next 20–30 years), all models project a steady increase of industrial final energy use, comparable to the IEA reference projection. In the long-term, however, there are clear differences in the projected trends, though these differences are not directly related to the different model assumptions described in Section 3. MESSAGE and GCAM project a continuous high growth of energy demand, DNE21+ (running until 2050), AIM/CGE, TIAM-UCL, and IMAGE show moderate growth and saturation of energy demand at the end of the century while POLES and Imaclim-R show reduction of energy demand in the second half of the century. In 2100, this results in a range of more than a factor 2 between the highest and the lowest projection. The ratio of final energy demand in 2100 compared to 2010 (2010 = 1) is between 3.4 and 1.4, which is comparable to final energy range of the much larger set of industry

⁵ Simulation models may in turn use an optimization routine at a given time steps: for instance, CGE models usually optimize welfare. Or else, they may use a more behavioral or descriptive routine that do not rely on optimization, such as a logit function to describe the evolution of technology shares.

⁶ A more in depth description of the models in general and more specific details on their representation of the industrial sector can be found in the [Supplementary Material](#).

Table 2

Main industry model characteristics. Information acquired primarily from the FP7 EU ADVANCE industry models stock taking.

IAM	Industry sector drivers	Industrial sub-sector breakdown	Technology	Efficiency improvements	Policy measures	Policy impact	Material trade (industrial goods)	Stock turnover	Recycling	Energy use as feedstock	Energy use in coke oven and blast furnaces ^c	Process emissions ^d
AIM-CGE	CES production function with the energy nested with value-added	Iron and steel, ^b chemicals, ^b non-metallic minerals, ^b food processing, pulp and paper, ^b construction, others (7)	No	CES nesting structure determines the technological energy efficiency and fuel use.	Carbon tax or emission constraint with carbon tax.	Price mechanisms	Yes	No	No	Only iron & steel	Only blast furnaces	From cement
DNE-21+	Material demand is related to production, consumption, import, export, population and GDP.	Iron and steel ^a , cement ^a , pulp and paper ^a , aluminium, some chemicals ^a (ethylene, propylene and ammonia) (6)	Yes	Exogenous per technology. More efficient technologies get a larger market share in response to higher fuel prices.	Carbon pricing, efficiency standards, and sectoral intensity targets.	Implementation rates of technologies and price mechanism	Yes (exogenous scenario)	Yes	Yes	Yes	In steel sector: Yes, other sectors: No	From cement, iron, etc.
GCAM	Endogenously from land use model (for fertilizer), and total GDP (for the remaining industry).	Cement ^a , nitrogenous fertilizers ^a , others (3)	No, only for CCS	Technology improvement rates take into account the opportunities for improved energy efficiency, and are a scenario input assumption.	Carbon taxes, emission constraints.	Modified fuel choices, production technologies and demands for industrial goods.	No	No	No	Yes	Yes	From cement
Imaclim-R	Exogenous drivers: population, productivity, resources Endogenous drivers: structural change, production, consumption preferences, import, export, energy prices	Energy-intensive vs. non energy-intensive industries.	No, only for CCS	Improvement of energy intensity depends on price development. Part is autonomous, and part is endogenous, induced by energy prices.	Carbon/energy taxes (or energy subsidies), emissions permits	Price mechanisms	Yes	Yes	Yes, but not explicitly	Yes	Yes	No
IMAGE	Material demand is related to economic activity and material intensity for steel and cement; energy intensity for other sectors.	Steel ^a , cement ^a , other (3)	Steel, cement	Exogenous per technology more efficient technologies get a larger market share in response to higher fuel prices.	Carbon tax, prescribing certain efficient technologies	A dynamic response to changed technology costs (incl. fuel price) or prescribed technology mix	Yes, only for cement and steel	Yes	Yes	Yes	Yes	From cement
MESSAGE	Total energy demand is related to GDP and population, based on historical energy intensity trends.	Thermal and electric demand of total industry, non-energy use, cement process emissions	No, only CCS for process CO ₂ emissions explicitly represented	Improvement of energy intensity depends on long-term price development. Fuel switching implies efficiency changes. No explicit representation of energy efficiency technologies.	GHG and energy pricing, GHG emission cap, permits trading, fuel subsidies, capacity, production and share target regulations	Price mechanisms and model constraints	No	No	No	Yes	In steel sector: yes, other sectors: no	From cement
POLES					Price mechanism		Yes		No	Yes		

Energy demand in industry depends on energy costs (short and long term effects) and an activity variable that is sub-sector dependent.	Iron and steel ^a , chemicals and petrochemicals ^b , non-metallic minerals ^b , others (4)	Boilers are described with a fixed cost, an efficiency and a life-time	Improvement of energy intensity depends on long-term price elasticities. No explicit representation of energy efficiency technologies.	Taxation policy on energy fuels, which includes carbon pricing.	(only for boilers)	Only own energy use in blast furnaces	From cement
TIAM-UCL GDP and other economic activity to derive energy demand or material demand.	Pulp and paper ^a , chemicals ^b , iron and steel ^a , non-metallic minerals ^a , others (5)	Yes	Exogenous per technology more efficient technologies get a larger market share in response to higher fuel prices.	Carbon tax/cap, permit trading, technology subsidy, efficiency requirements	Yes, but not explicitly modeled	Yes	No

^a Modeling physical production and energy demand of the sub-sector.

^b Modeling energy demand of the sub-sector.

^c Transformation and own energy use.

^d The process emission that can be assigned to a specific sub sector.

sector scenarios shown by the IPCC over the 21st century [5], which includes 120 baseline scenarios.

Disaggregating the results between regions, shows that the final energy consumption pathways in Non-OECD countries is crucial in understanding these global trends (Fig. 2c). All models project annual industrial final energy use in OECD countries to remain more or less constant compared to current values, while in Non-OECD countries industrial energy use is projected to grow significantly. The United States Energy Information Administration (U.S. EIA), in its 2016 International Energy Outlook study, projects that total industrial energy use will increase in the period 2012–2040 at an annual rate of 0.5% and 1.2% in the OECD and Non-OECD countries, respectively [21]. Total energy use is estimated to reach 326 EJ in 2040; a higher estimate than in the models in this study.

The development of the baseline scenario is very important in our attempt to make reliable estimations of the potential for GHG mitigation and its impacts. Although all models project final energy use to increase in Non-OECD countries, how long this growth will continue is a key uncertainty across models. Recent research [22] showed that the demand for cement in China, a key Non-OECD country, is expected to reach a peak in the coming years and start very soon a declining trend, a key development that current models might not be able to capture (described in more detail in section 5).

4.1.2. Energy intensity trends

Changes in industrial energy intensity (i.e. the ratio between sectoral energy use and GDP or sectoral value-added) can be the result of economic structural change (different growth rates of different economic sectors and shifts towards higher-value goods produced by the industrial sector) and improved energy efficiency. Literature suggests that a key factor in the energy intensity decline in developing countries has been technological change while in developed countries the shift towards high-tech industry [3,23]. Moreover, the share of Industry Value Added (IVA) in GDP has decreased in OECD countries which decreased the energy intensity compared to GDP even further, as can be seen in Fig. 3.

The models project energy intensity (w.r.t. GDP) of Non-OECD countries in the coming century to decline with annual reduction rates ranging from 1.8 to 2.2%. These are significantly larger than the average reduction rate of 0.6% measured empirically between 1970 and 2010. In OECD countries energy intensity continues to decrease, but with lower annual reduction rates varying between 0.3 and 1.7%, compared to the historic average of 2.7%. As mentioned, this historical reduction in OECD countries is largely the result of reducing IVA share in GDP. A key uncertainty for future industrial final demand is thus whether energy intensity in Non-OECD countries converges to the historically observed OECD levels.

4.1.3. Energy consumption by fuel type

Fig. 4 shows the projected industrial final energy use per fuel type for the years 2010, 2030, 2050 and 2100. The AIM/CGE and IEA results do not include industrial feedstock use. Interestingly, there is a reasonably high agreement of the modeled fuel shares across the models, remaining close to current shares. Fossil fuels are projected by all models to take up more than 50% of the industrial fuel use in 2100. Most models, except Imacim-R and TIAM-UCL project a slight increase in electricity use and a decrease in fossil fuel use, both between 10 and 20% change. The electricity and gas shares in the models are relatively low compared to IEA scenarios, projecting respectively 31 and 21% in 2030.

4.2. Mitigation scenario projections

In the stringent climate policy scenario, all models show a decrease in final energy demand compared to the baseline (Fig. 5

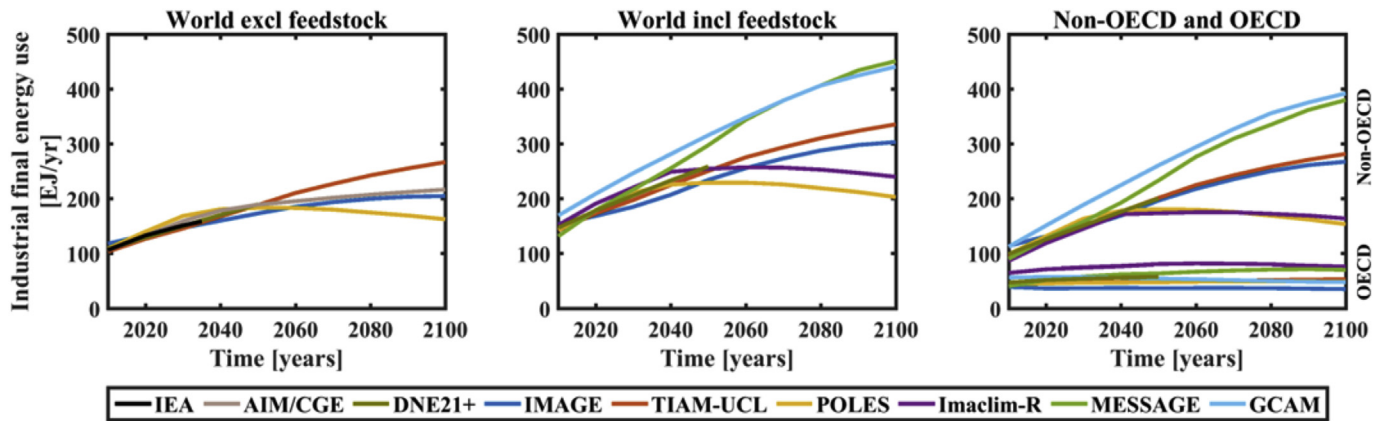


Fig. 2. Baseline final energy demand projections in the industry sector up to 2100: a) Global excl. feedstock, b) Global incl. feedstock and c) Non OECD and OECD countries incl. feedstock.

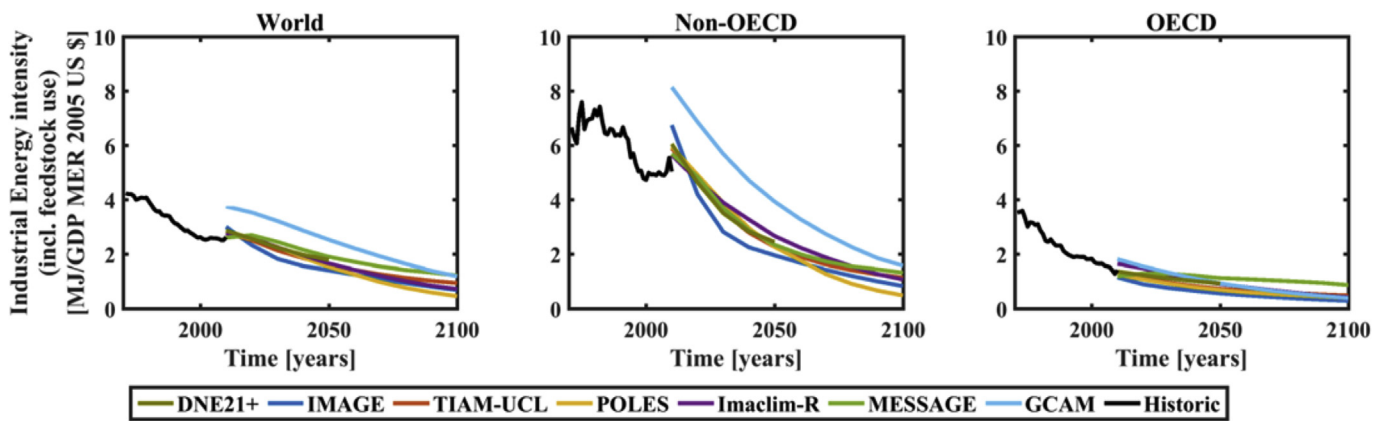


Fig. 3. Industrial energy intensity expressed in final energy use/GDP MER (in USD \$2005) for different regions: a) global, b) Non-OECD countries and c) OECD countries. 1970–2005 historic energy intensity values [24] are shown in black.

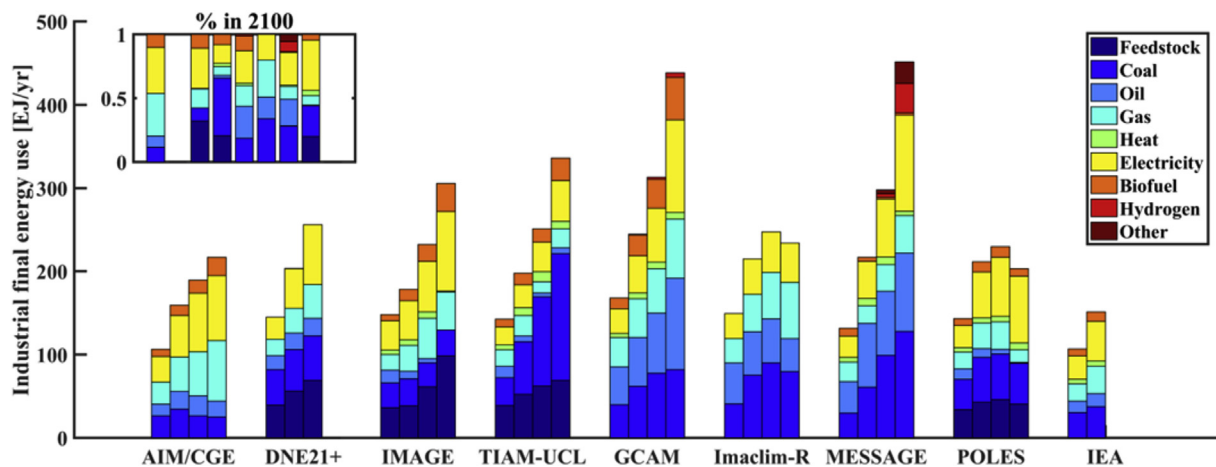


Fig. 4. Baseline final energy demand of the industry per energy carrier in 2010, 2030, 2050 and 2100. The reported values include feedstock use for MESSAGE, GCAM and IMACLIM, which in 2010 is mainly oil use in the chemicals and petrochemicals sectors, and cokes in the iron and steel sector. In the top left the fuel shares in 2100 are shown.

left panel). The range of projected industrial final energy use in 2100 drops from 203–451 EJ to 115–306 EJ, i.e. a reduction of 10–50%. The IEA projects a reduction of 18% in 2035. TIAM-UCL, GCAM and MESSAGE project a more or less constant reduction in time, while IMAGE, POLES, AIM-CGE and Imaclim-R show a high reduction in the first 50 years and continue with a steady

percentage. Interestingly, the models with low industrial energy demand (with the exception of TIAM-UCL) in the baseline find that there is potential to decrease the industrial energy intensity even further to reach a climate target, and this decrease occurs in those models more rapidly in the coming decades than in the other models.

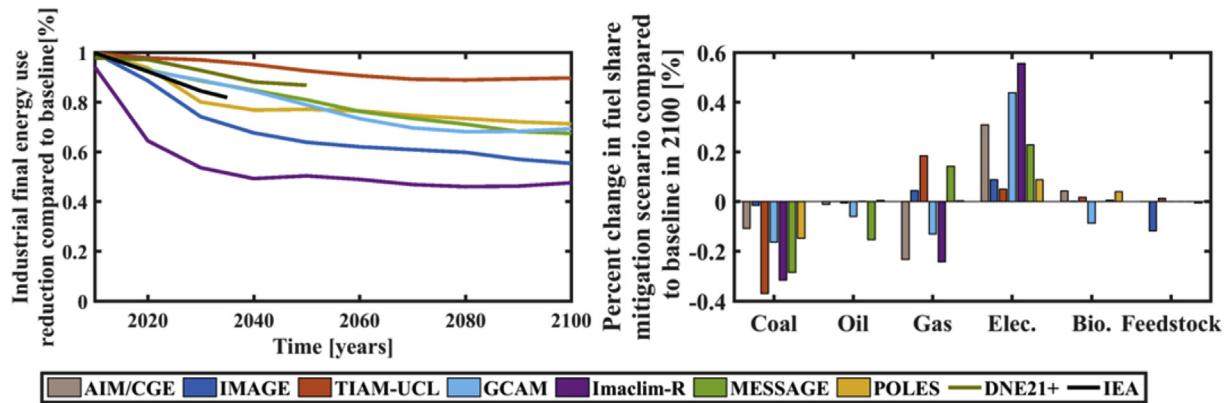


Fig. 5. a) Mitigation scenario final energy demand as a portion of the baseline scenario final energy demand and b) Percent change in fuel share mitigation scenario compared to baseline.

The fuel mix changes significantly in the mitigation scenario which can be seen in Fig. 5b, showing the percentage change in fuels shares in 2100 between a mitigation scenario and a baseline scenario (indicating how flexible the model is to switch to different fuels as a response to higher fossil fuel prices). All models except IMAGE show a strong decline in fossil fuel use in the mitigation scenario. More specifically, especially coal use is reduced while electricity increases. TIAM-UCL and MESSAGE also show a switch from coal to gas.

In all models, there are no large changes in oil and biomass shares. The apparent shift towards electricity is significantly larger for AIM/CGE, GCAM, Imaclim-R and MESSAGE than other models. These models in fact have little explicit technology detail, which could explain a higher flexibility in fuel switching. In technology-rich models, additional information is added to the models on preferred fuels for different processes. Moreover, in the latter type, improvements are bounded by the technologies represented in the model which could constrain options for fuel switching.

The differences in model behavior highlight the issue of the appropriate level of detail and the specifics of the manufacturing technologies used. In this exercise, the more aggregate models tend to represent many industrial sub-sectors together with generic production technologies in which all fuels are substitutes. Process-based, technologically detailed models may not include the capacity for future fuel-switching based on current technical information. In the past, we have seen examples of both restrictions in fuel-switching as well as flexibility (e.g. introduction of electric arc furnaces in the steel industry).

The different approaches to reduce these industrial emissions are summarized in Table 3. Variations across models lie in the extent and rapidness of energy intensity reduction, and flexibility

to switch fuels as discussed in the previous paragraphs. In models where both approaches have a limited application (e.g. TIAM-UCL, MESSAGE), other sector's emission budget will be more constrained.

5. The cement industry – sub-sector model comparison

In this section we take a closer look into the projected material production and energy use for the cement industry to get a better impression of how the industrial sub-sectors are represented in the models. The models included are IMAGE, DNE21+, AIM/CGE, POLES, GCAM and TIAM-UCL. The analysis focuses on the baseline scenario, while for comparison, also the IEA projection for the 6 °C scenario (6DS) is shown [4].

The reason to focus on the cement industry is that it represents a considerable share of global industrial energy consumption and GHG emissions. In 2009, the global cement industry consumed 11 EJ, which is 11% of global industrial energy consumption (excl. feedstock use) and emitted 2.3 GtCO₂ which is 26% of global industrial GHG emissions of which more than half were process emissions from calcination [25]. Several studies have identified technologies/measures that can limit the energy use and GHGs, and improve material efficiency in this sector [26–28]. Another reason to focus on this sector is that compared to the other major energy intensive industries, the cement industry is less complex. Cement is almost entirely used by the construction industry. Cement plants globally use the same three process steps i) raw material preparation, ii) clinker calcination, and iii) final material preparation. In addition, trade between the different countries is limited as cement transportation is very costly. In 2009, only 4.5% of cement consumption was traded [29], meaning that for most countries, and certainly the large regions covered in models, cement production is equal to cement consumption.

Fig. 6a shows the projected production of cement in GCAM and IMAGE, the production of non-metallic minerals in TIAM-UCL and the production of clinker in DNE21+, that model material use explicitly. The global cement production in 2010 was 3.2 Gtonnes [30] and the global estimated clinker production was 2.4 Gtonnes (based on a clinker to cement ratio of 76%)⁷ [31]. The IEA shows a

Table 3

Annual reduction (%) with respect to 2010 of energy intensity, CO₂ intensity and CO₂ emissions in the models mitigation scenario. The relatively high values are marked bold.

	Energy intensity (MJ/\$)		CO ₂ intensity (g/MJ)		CO ₂ emissions	
	2050	2100	2050	2100	2050	2100
DNE21+	1.45		1.23		0.12	
IMAGE	2.95	2.25	1.60	1.55	1.66	1.45
TIAM-UCL	1.53	1.30	0.85	0.91	−0.38	0.08
POLES	2.09	2.31	1.54	1.78	1.01	1.77
Imaclim-R	2.79	2.20	1.93	1.78	2.21	2.03
MESSAGE	1.30	1.26	1.93	1.78	0.43	0.86
GCAM	1.56	1.66	1.84	6.91	0.89	6.29

⁷ Although there is data available on cement production, data on clinker production is not. Therefore, clinker production is usually estimated based on information concerning the clinker to cement ratios. The clinker to cement ratio reported by the WBCSD/CSI (2012) is lower from the clinker/cement ratio of 80% reported in IEA (2012b). For an 80% clinker/cement ratio, the 2010 clinker production would be 2.56 Gtonnes.

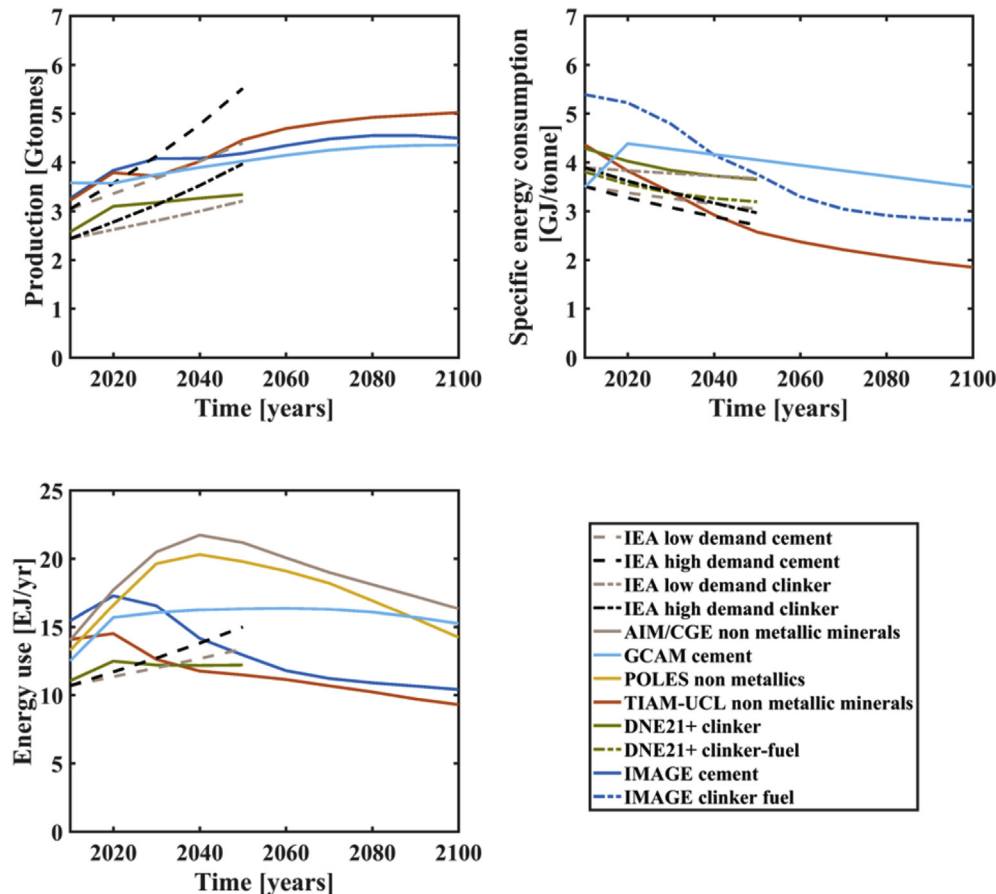


Fig. 6. a) Projected material production in the non-metallics/cement industry b) energy use c) specific energy consumption for cement and clinker making in different long-term energy models under the baseline scenario in comparison with the IEA projections.

relatively high increase in clinker production in both the low demand and the high demand scenarios compared to the other three models. It should be noted that different calibration years do influence the results (e.g. IMAGE is calibrated to 2005). Above all, all long-term energy models show a saturation of demand, while the IEA seems to project a steady growth. In IMAGE, there is a peak in global cement production at around 4 Gtonnes taking place in 2030; where after cement production remains stable to slightly increase after 2040 to reach a new plateau at 4.5 Gtonnes. In GCAM, a similar development is noticed although in the first decades cement production does not grow as strong.

Making reliable estimates of the cement industry developments under a baseline scenario is key in the analysis of GHG abatement potentials. In the case of the Chinese cement industry, it has been observed that using pure economic drivers for the projection of cement demand, resulted in higher projections than when using physical drivers [32]. In a recent study of the Chinese cement industry [22] that uses the development of the different construction activities as physical indicators and cement intensities per type of construction to account for the cement needed in urbanization and industrialization processes, Chinese cement production is estimated to peak in 2017 at 2.5 Gtonnes. For the coming 10 years it was forecasted that a slow decrease will follow while from 2030 to 2050 cement production will decrease from 2.3 to 1.5 Gtonnes, respectively. In IMAGE, Chinese cement production peaks in 2020 at 1.5 Gtonnes and decreases to 0.6 Gtonnes by 2050; however it needs to be noted that in IMAGE, an earlier year was used for calibration that did not take into account the strong growth observed in recent years.

The projected energy demand for the non-metallics/cement industry by IMAGE, GCAM, TIAM-UCL and DNE21 + peaks relatively early and then levels off or even declines (Fig. 6b). AIM/CGE and POLES project the energy demand to peak at a much later year (2040) after which also a decline is observed. The IEA projections show continuous growth rates (driven by the rapid increase in demand for cement). The models show again differences in base year data. All models project that the cement sector share in total industrial final energy use decreases.

Fig. 6c shows the development of specific energy consumption (SEC) for cement and clinker making in the various energy models. This is projected to decline in all models driven by technology development (with exception of the GCAM results for the first 20 years of the projection). In IEA, the 2009 energy use for cement making, 3.5 GJ/tonne cement, is forecasted to drop to 3.1 and 2.7 GJ/tonne by 2050 under the low and high demand scenarios, respectively. In clinker making, the energy use (mainly fuel) is projected to decline from 3.9 GJ/tonne clinker in 2009 to 3.7 and 3.0 GJ/tonne clinker in 2050 in the low and high demand scenarios, respectively [4]. That is an annual decrease in the specific energy consumption of clinker calcination of 0.14 or 0.66%.

The annual decline rates of the specific energy consumption during the 2010–2050 period, for clinker/cement/non-metallics production are about 0.40%, 0.42% and 1.31% for DNE21+, IMAGE and TIAM-UCL respectively while the IEA scenarios show a range of 0.56–0.85% for cement making. Literature suggests that the energy use for clinker making can drop to 2.9 GJ/tonne clinker [27] and when improved equipment for cement making and lower clinker to cement ratios are used the energy use could drop to 2.1–2.7 GJ/

tonne cement [4,33]. This means that considerable improvement of the energy efficiency would still be possible in the mitigation scenarios compared to the baseline projections.⁸

6. Discussion and conclusion

6.1. Discussion

Overall, the industrial sector representation in long-term energy models has revealed some striking similarities in the projected energy use pathways. Energy intensity (w.r.t GDP) in Non-OECD regions is projected to decrease more rapidly over the coming century than the one observed in recent decades with annual reduction rates varying between 1.8 and 2.2%, compared to average annual reduction of 0.6% between 1970 and 2010, which is a clear trend break. OECD countries final energy use remains close to current energy use ranging between 36 and 71 EJ/yr in 2100 across the models. Similarly, industrial fuel shares remain close to current values, with electricity use increasing slightly and fossil fuel use decreasing, both between 10 and 20% change.

Despite these similarities, projected industrial carbon emission pathways cover a broad range across the models (between 7.5 and 24 Gt/yr in 2100). This can be explained by already different base year assumptions in fuel shares, energy consumption and accompanying emissions, as well as diverging trends of final energy consumption in Non-OECD countries in the second half of the century. These differences could be significantly larger if for example Non-OECD countries would not decouple so strongly from GDP as seen in current projections, or if there is a higher shift to electricity. In addition, model results could be different if non-monetary drivers are used to project material demand.

To assist the result comparison, describing in detail how the industrial module works and thereby increasing transparency in each model is of great importance. The base year final energy data differs per model and in order to make a credible comparison, reporting the industry boundaries is important. Feedstock use accounts for 17% of industrial energy consumption and it should be clear whether it is accounted for. The same holds for the energy use in coke ovens and blast furnaces and in refineries. In the cement/nonmetallic comparison the same effect is visible but by specifying which production processes are accounted for, the variation can be clarified.

The mitigation scenarios show that models employ different strategies to mitigate emissions. Some models show a significant reduction of final energy demand in the coming decades, while other models remain close to their baseline final energy levels and rely more on fuel shifting. Comparing long-term energy models at the sub-sector level, such as done in this analysis for the cement sector, can improve our understanding of differences and similarities underlying the model projections. Moreover, comparing bottom-up model details to sector-specific case studies could improve projections, and increase the ability to assess sector specific mitigation policies—at least in the short term. For example, comparing the projected SEC of cement production to state of the art knowledge shows that in mitigation scenarios there is indeed scope to considerably reduce energy demand compared to the models' baseline scenarios.

Using energy intensities of specific countries/regions, in combination with projected material demand to model industrial future energy consumption can help to better understand the role of

recycling, material efficiency, and technology efficiency in mitigating emissions. This allows to better estimate what levels of energy intensity improvements are reasonable to achieve, which share of the energy use can be replaced by less carbon intensive fuels, and how fast both processes could take place. For example, by improving the material efficiency in cement making with the use of higher amounts of supplementary cementitious materials at different stages of cement production. On the long term, constraining industrial technology change to what is currently known might be detrimental, as unknown technology options are not accounted for.

Accounting for material demand at sub-sectorial level has as additional advantage that, in the integrated structure that global system models operate, it provides the opportunity to relate the material demand to activities that require material, which are also represented in the model. An example would be to relate cement demand to future infrastructure and building requirements, which could give more guidance and better projections for material demand saturation.

6.2. Main conclusions

Based on the comparison, a number of key conclusions can be drawn.

In the reference baseline scenario, the overall trends across the models are comparable in the coming decades: the industry sector is relatively energy intensive and remains reliant on fossil fuel (>50%). The annual increase in the models ranges from about 1.2 to 1.4% per year for the full model range (including the IEA projection).

In the long-term, there is a large divergence in industry sector energy consumption mostly based on the question whether models project either a continuous growth or saturation. This leads to more than a factor of 2 difference between the highest and the lowest industrial energy demand projection in 2100. The 2100 energy consumption ranges between 203 and 451 EJ/yr across the models. Saturation of industrial energy demand depends strongly on whether Non-OECD countries are projected to reach similar energy intensity levels as achieved in OECD countries, which is a key uncertainty across models.

Models show different responses to mitigate CO₂ emissions, where uncertainties are the potential of fuel switching or energy intensity improvements. The reduction of final energy use in 2100 compared to the baseline scenario spans a range of 10–50%. The models show a switch from coal to electricity use as a measure to reduce industrial emissions. Interestingly, models that explicitly model industrial technologies seem to be more constrained in the flexibility to use different fuel types, as shown in the mitigation scenario results. This divergence highlights that the understanding of economy-wide mitigation responses and costs is an area for future improvement in the models.

Using industry sub-sector material and energy use details to support the projected mitigation potential can provide insight in feasibility of how emission reductions can be achieved. More information at a sub-sector level could improve the understanding of what are the realistic energy intensity improvements as a result of material usage and technology efficiency changes in the short term, along with the potential to use less carbon intensive fuels. Moreover, this would create the opportunity to relate material demand to non-economic drivers, such as infrastructure growth and building stock turnover to improve the understanding of demand saturation and assess the role of sub-sector specific climate policies to mitigate emissions.

⁸ The IMAGE energy intensity values are relatively high due to the use of outdated regional data (calibration was done until 2005) on historical energy intensity and clinker to cement ratios.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.energy.2017.01.017>.

References

- [1] IEA. Energy Balances of non-OECD countries 2012 edition with 2011 data. 2012 [Paris, France].
- [2] IPCC. Industry. In: Fischelick JRM, Abdel-Aziz A, Acquaye A, Allwood JM, Ceron J-P, Geng Y, et al., editors. Climate change 2014: mitigation of climate change. Contribution of working group iii to the Fifth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2014.
- [3] UNIDO. Industrial energy efficiency for sustainable wealth creation. Capturing economic and social dividends. United Nations Industrial Development Organization; 2011.
- [4] IEA. Energy technology perspectives 2012–pathways to a clean energy system. 2012 [Paris, France].
- [5] IPCC. Assessing transformation pathways. In: Clarke KJ, Akimoto LK, Babiker M, Blanford G, Fisher-Vanden K, Hourcade J-C, et al., editors. Climate change 2014: mitigation of climate change. Contribution of working group iii to the Fifth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2014.
- [6] Sugiyama M, Akashi O, Wada K, Kanudia A, Li J, Weyant J. Energy efficiency potentials for global climate change mitigation. *Clim Change* 2014;123(3–4): 397–411.
- [7] Liu N, Ang B. Factors shaping aggregate energy intensity trend for industry: energy intensity versus product mix. *Energy Econ* 2007;29(4):609–35.
- [8] OECD. OECD science, technology and industry scoreboard 2011: innovation and growth in knowledge economies. 2011 [Paris, France].
- [9] Kriegler E, Riahi K, Bauer N, Schwanitz VJ, Petermann N, Bosetti V, et al. A short note on integrated assessment modeling approaches: rejoinder to the review of “Making or breaking climate targets—the AMPERE study on staged accession scenarios for climate policy”. *Technol Forecast Soc Change* 2015;99: 273–6.
- [10] van der Zwaan BC, Rösler H, Kober T, Aboumahboub T, Calvin KV, Gernaat DEHJ, et al. A cross-model comparison of global long-term technology diffusion under a 2 °C climate change control target. *Clim Change Econ* 2013;4(04):1340013.
- [11] Kriegler E, Weyant JP, Blanford GJ, Krey V, Clarke L, Edmonds J, et al. The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. *Clim Change* 2014;123(3–4):353–67.
- [12] Calvin K, Clarke L, Krey V, Blanford G, Jiang K, Kainuma M, et al. The role of Asia in mitigating climate change: results from the Asia modeling exercise. *Energy Econ* 2012;34:S251–60.
- [13] Rosen RA, Guenther E. The economics of mitigating climate change: what can we know? *Technol Forecast Soc Change* 2015;91:93–106.
- [14] Girod B, van Vuuren DP, Grahn M, Kitous A, Kim SH, Kyle P. Climate impact of transportation A model comparison. *Clim Change* 2013;118(3–4):595–608.
- [15] Calvin K, Wise M, Klein D, McCollum D, Tavoni M, van der Zwaan B, et al. A multi-model analysis of the regional and sectoral roles of bioenergy in near- and long-term CO₂ emissions reduction. *Clim Change Econ* 2013;4(04): 1340014.
- [16] Zhang S, Worrell E, Crijns-Graus W. Synergy of air pollutants and greenhouse gas emissions of Chinese industries: a critical assessment of energy models. *Energy* 2015;93:2436–50.
- [17] Sathaye J. Bottom-up representation of industrial energy efficiency technologies in integrated assessment models for the cement sector. 2011.
- [18] IEA. World energy outlook 2013. IEA; 2013.
- [19] Löschel A. Technological change in economic models of environmental policy: a survey. *Ecol Econ* 2002;43(2):105–26.
- [20] Allwood JM, Ashby MF, Gutowski TG, Worrell E. Material efficiency: a white paper. *Resour Conserv Recycl* 2011;55(3):362–81.
- [21] Doe-Eia US. International energy outlook 2016. 2016 [Washington, DC].
- [22] Li N, Ma D, Chen W. Projection of cement demand and analysis of the impacts of carbon tax on cement industry in China. *Energy Procedia* 2015;75: 1766–71.
- [23] Olivier J, Janssens-Maenhout G, Muntaen M, Peters J. Trend in global CO₂ emissions. Bilthoven, the Netherlands: PBL Netherlands Environmental Assessment Agency; 2013.
- [24] IEA. Energy Balances of OECD countries 2015 edition. International Energy Agency, Paris France; 2015.
- [25] IEA. Energy Balances 2011 edition with 2009 data. 2011 [Paris, France].
- [26] WBCSD/CSI-ECRA. Development of state of the art-techniques in cement manufacturing: trying to look ahead. Dusseldorf, Geneva: World Business Council for Sustainable Development/Cement Sustainability Initiative-European Cement Research Academy; 2009.
- [27] JRC/IPTS. Prospective study on long-term energy systems – POLES manual version 6.1. Joint Research Centre; 2010.
- [28] Worrell E, Kermeli K, Galitsky C. Energy efficiency improvement and cost saving opportunities for cement making: an energy star guide for energy and plant managers. United States Environmental Protection Agency (U.S. EPA); 2013.
- [29] Harder J. Outlook on the global cement and clinker trade. *ZKG Int* 2008;61(6/36).
- [30] USGS. Minerals yearbook – cement [advance release]. 2013. Washington, D.C., United States: United States Geological Survey; 2011.
- [31] WBCSD/CSI. Global cement database on CO₂ and energy information. World Business Council for Sustainable Development/Cement Sustainability Initiative; 2012.
- [32] Ke J, Zheng N, Fridley D, Price L, Zhou N. Potential energy savings and CO₂ emissions reduction of China's cement industry. *Energy Policy* 2012;45: 739–51.
- [33] Kermeli K, Graus WH, Worrell E. Energy efficiency improvement potentials and a low energy demand scenario for the global industrial sector. *Energy Effic* 2014;7(6):987–1011.