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Improving energy demand modelling in integrated assessment models

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Finally, we would like to highlight that several paragraphs in this report have already been published or are planned to be published in peer reviewed journals.

Summary

Integrated assessment models (IAMs) tend to have a relatively stylized representation of energy demand sectors and significantly more detail energy supply modules. An important reason for this is that energy demand sectors typically are complex, and therefore relatively difficult to capture by morels. They are characterized by many sub sectors, with a large number of very specific technologies and heterogeneity of consumers that affect future energy demand projections. Still the aggregated representation of energy demand in current IAM models suggests that energy demand can have a major contribution to emission savings.

In Work Package to of the ADVANCE Project we made an effort to improve the representation of energy demand sectors in integrated assessment models (IAMs), by incorporating more detailed end use models for specific sectors. Two tasks were distinguished in order to do so:

- **Enhanced representation of demand for energy services**. This will be done by identifying major energy end use services and the end use specific drivers. For this task a key set of indicators (e.g. in the cement sector tonne cement produced) have been used, to compare model results to each other and increase our understanding of model dynamics.
- **Enhanced representation of the scope of increased efficiency**. This second task focusses on the technology options to fulfill the service demand and the specifically look at the opportunities to increase energy efficiency and switch to alternative fuels. Not all IAMs include such detail in their energy demand representation, the two tasks will also focus on translating the more detailed energy demand models in to meta relationships for aggregated models.

The work has been divided over the three main energy demand sectors: Transport, Industry and Buildings. In this report, we report on the work done in each sector. Each of the following chapters looks in to the modelling of a specific sector. The chapters first present an overview of the sector modelling in the IAMs participating in ADVANCE at the start of the project. Next, the sector specific dynamics and challenges to mitigate emission are discussed leading to objectives with respect to model development. Those model developments that taken place during the ADVANCE project are thereafter described in more detail within the specific model. Finally, per sector a model comparison of baseline and a climate policy scenario is presented, where the focus is on underlying sectorial developments such as activity growth, structural change and technological change.

<u>Transport</u>

A large share of the model development has taken place in the transport modules, where capturing technology development, mode choice and shift, infrastructure capacity and costs, consumer heterogeneity and behavior have been identified as areas where improvements can be made. By including these details the aim is to improve the models representation of the transport sector and its ability to transition to low carbon intensive options with potential pitfalls and opportunities. Moreover, including more detail in these processes offers the ability to address sector specific policies. Examples can be energy efficiency standards or technology regulations.

As a second step has been to compare IAMs transport scenarios in two separate studies: one using kaya identities to compare scenarios and the second addressing the models inherent price elasticities. In the first the focus is on the development of Activity growth (pkm/cap), Structural change, Energy intensity (MJ/pkm) and Fuel mix (g/MJ) in passenger transport. In all models energy efficiency and fuel mix change play a major role in decreasing emissions in the carbon policy scenario, and in some models activity decrease as well. Most models represent different passenger modes, however mode shift throughout the century is limited in the baseline scenario, and plays a limited role in decreasing emissions in the climate policy scenario. An important factor in transport scenarios is that it is unclear at what point activity demand saturates, which can be seen in the range

of activity projections across models. Varying projections of technology development of alternative drive train vehicles in terms of cost and efficiency lead to different fuel mix and efficiency potentials.

The transport models have been tested through fuel price shock scenarios to compare the models price demand response. This exercise consists of 16 scenario with shocks of -50%, 50% and 100%, with respect to the baseline applied to Oil & Gas, Coal, Biofuel and Electricity. The analysis has focused on transport sector oil prices, but it can be applied to other demand sector as well. Ten years after the shock implementation, although there is a significant range between the models, the oil demand elasticities are comparable to empirically found historical gasoline price elasticities. Thirty years later in 2060 model results are less straightforward to compare. In some models the price effect has reduced significantly as a result of feedback effects, while in other models this is not the case. The scenario-set up gives insight in whether the models are responsive or less responsive to changing fuel prices and response timing, and the analysis will be extended to other demand sectors and fuel prices as part of Deliverable 3.4 of ADVANCE.

Buildings sector

Buildings model development has focused on explicit representation of energy functions in residential or services sector buildings, such as space heating, space cooling, lighting and appliances. Modelling this detail has as advantage that end use demand can be related to climate conditions, and thus capture regional differences. Moreover end use specific efficiency and fuel switching opportunities, and structural change can be accounted for. To improve our understanding of how this affects buildings scenario results, the model comparison has focused on the breakdown of functions in the residential models.

- The models all show a strong shift towards electricity in baseline and even more in carbon tax scenario, and the decrease in total emission (incl. indirect) is highly dependent on the CO2 intensity factor of electricity production.
- Models with an explicit representation of energy functions taken into account in this study seem to be less able to substitution to electricity than models without this detail in a carbon tax scenario. This effect, however, is moderate. In a scenario aiming to achieve a 450 ppm target result in a more than 65% share of electricity in 2100 in all models.
- Modelling energy functions allows explicit representation of functional change (e.g. more cooling and appliances) in the future, distinguishing between regions, and representing energy efficiency potential per function. It is however uncertain how these pathways will develop. An improved understanding of these changes would be an important next step in model development.

Industry

The cement and iron and steel sector have been selected as key industrial sectors for improved modelling, as both sectors have a large contribution to industrial GHG emissions, and are very policy relevant. For both sectors the modelling challenges are presented. For the cement sector an elaborate description of the cement demand drivers, and how they relate to cement production, the production process and key opportunities to reduce material use, energy use and GHG emissions are discussed. In the IMAGE cement module based on the cement modelling guideline an update of cement demand projections have been made, and a more elaborate description of production technologies is incorporated.

Finally, an in depth comparison of the industrial sector representation is performed to understand by what means industrial emissions are reduced, and where uncertainties in model projections lie.

In the baseline scenario, the projected behavior across the models is comparable in the coming decades: the industry sector is relatively energy intensive and remains reliant on fossil fuel (>50%). In the second half of the century however the models project either continuous growth or saturation. Comparable to the transport sector findings saturation of demand is uncertrain. This leads to more than a factor 2 difference between the highest and the lowest industrial energy demand projection in 2100. Saturation of industrial energy demand depends strongly on whether regional differences remain, and Non OECD countries will reach similar energy intensity levels as achieved in OECD countries.

Models show different measures to mitigate CO_2 emissions, similar to findings in the transport or buildings sector, uncertainties lie in the potential of fuel switching or energy intensity improvements. The models switch from coal to electricity use to reduce industrial emissions. Modelling industrial technologies can constrain the flexibility to use different fuel types and this is recognized in the mitigation scenario results, where technology rich models show less fuel switching as a measure to mitigate GHG emissions.

Understanding energy demand subsector (at transport mode, energy function or industry product level) details to support the projected mitigation potential can provide insight in feasibility of how emissions reduction can be achieved. Historical data at this level is need to support the model base year and future projections. More information at a subsector level could improve the understanding of what realistic energy intensity improvements as a result of material usage, structural change and technology efficiency changes are, along with the potential to use less carbon intensive fuels.

1. Transport

1.1. Introduction

Since 1970 the transport direct GHG emissions have doubled in 2010 to 7.0 GTCO2eq, increasing at a faster rate than any other end use sector (IPCC WGIII Ch.8 R. Sims, 2014). The transport sector uses 28% of global total final energy demand, of which 95% comes from oil based fuels. 72.8% of the transport energy use is used for road transport. Population growth, expanding globalization, trade flows and increasing income and urbanization has led to increased demand for transport of goods and people, which in turn has often led to economic benefits, for example due to increased tourism (GEA Ch. 9 Kahn Ribeiro, 2012).

Innovation of motor vehicles and airplanes has rapidly induced mobile, flexible and accessible opportunities, which combined with intelligent communication systems has changed social interaction, lifestyles and is embedded in societal values. Mobility is nowadays related to high quality of life. Technical innovation has not increased mobility in all regions and populations, and large differences in mobility exist across regions. Where in more wealthy nations long distances can be travelled in a comfortable and reliable manner, in poorer regions with large income differences and often poor urban planning, people are faced with challenges to meet basic transport needs (Kahn Ribeiro, 2012)

Besides environmental effects of transport related GHG emissions, energy and resource use at a global level, the increasing mobility, and specifically individual motorized transport in urban areas, has resulted social and environmental impacts at a local scale. Examples are air pollution, noise, congestion, water and soil degradation, asthma, obesities, road deaths and social and urban fragmentation (Kahn Ribeiro, 2012). Strategies to decrease transport GHG emissions can therefore lead to co-benefits, such as increased public health (Woodcock et al., 2009).

Reduction of transport GHG emissions can be achieved through different types of intervention (Chapman, 2007; R. Sims, 2014):

(1) *Lowering transport demand*: Transport journeys could be avoided by urban planning, increase use of local production, use of information and communication technologies (ICT), and more efficient application of freight logistics.

(2) *Shifting transport modes*: Modal shift towards low carbon intensity modes such as public transport, walking and cycling, especially in the urban environment through smart infrastructure planning, has the potential to reduce emissions in the passenger transport sector. For freight transport shifting towards rail and waterborne transport offers potential for long distances.

(3) *Reducing energy intensity of technologies*: Energy intensity reduction in response to policy regulations in Japan, USA and Europe in the light duty vehicle sector (LDV) have proven that there is some potential for efficiency improvement of internal combustion engine (ICEs) and hybrid electric vehicles (HEVs). (Bandivadekar, 2008) indicates that the average 2007-2010 LDV fuel consumption can be reduced with at least 50% through measures like engine road reduction, and improving engine and drive train system performance.

In the freight sector there is room for technology and operational improvements of Heavy Duty Vehicles to reduce energy intensity in developed countries, and even more in developing countries, which in which relatively old and less efficient trucks are common. Rail and shipping are relatively efficient transport modes, and aircraft have increased energy efficiency in the last decades but optimizing load shape, weight, size and engine performance can improve the energy intensity even further. The introduction of hybrid electric drive trains in urban areas for busses and trucks that stop and go has high potential

(4) *Reducing carbon intensity of fuels*: Finally, fuel carbon intensity can be reduced significantly by introduction of alternative propulsion technologies, such as electric vehicles are fuel cell vehicles, or by using lower carbon fuels for combustion such as biofuels, or gas. The extent of the reduction depend on upstream emission of the fuel production during conversion processes and the feedstock used.

The discussed measures to transition to a low carbon transport sector, whether it is more efficient vehicles, advanced propulsion technologies, mobility avoidance, or modal shift are affected by policy measures, infrastructure development and behavioral change. They can be more applicable in the long term or the short term, and depend on urban planning, vehicle stock, technology developments.

These considerations, and possible scenarios, make the transport sector a very complex sector to model in Integrated Assessment Models.

The transport chapter is structured as followed: In the next paragraph is discussed how the transport sector is currently modelled in IAMs, with specific detail on mode demand and vehicle fleet representation. In paragraph 3 a general overview of transport model development directions and their policy relevancy is described, along with individual model development that has taken place within the ADVANCE project. Then, the model results are compared, through scenario analysis, focusing specifically on the GHG mitigation interventions discussed above (paragraph 4). Finally the scenario set-up and first results of price and income responsiveness exercise is presented (paragraph 5).

1.2. Stocktaking – description of current transport models

Overview of the IAM Transport modelling

At the start of the ADVANCE project a qualitative questionnaire was send out to the modelling teams to take stock of the transport sector representation in IAMs. TIAM-UCL, IMAGE, Imaclim-R, MESSAGE, REMIND, GCAM, AIM-CGE, DNE 21+, WITCH, POLES and iPETs participated in this stocktaking exercise. Table 1 and Table 2 provide a summarized overview of the responses. The participating IAMs differ in sectoral coverage, structure and solution method. Most models use a hybrid approach to model the energy demand of the transport sector, combining a top-down transport demand formulation with the explicit modelling of modes and technology options per mode.

A few models relate the demand per mode to mode speed, attempting to capture modal shift dynamics. MESSAGE and IMAGE both use travel money budget (TMB) and travel time budget (TTB) as top down element, in combination with the price and speed of the modes to project transport service demand per mode. GCAM uses a similar approach, where the speed of the transport mode and vehicle operating cost affect the services prices, which is brought in relation to GDP to determine the energy service demand. Imaclim-R uses time spent travelling as a demand constraint as well, assuming that the mode speed is affected by utility of infrastructure. A second constraint to demand revenue to maximize utility, which are affected by the mode price.

In POLES, DNE21+ and TIAM-UCL GDP per capita is related to modal service demand. In REMIND, WITCH, and AIM-CGE service demand is derived in a top down fashion, where transport energy demand is input to a production function driven by GDP growth. The iPETs model household consumption of final goods, which includes transport, is derived from income and (optimized) savings. More details on how the energy demand is modeled in the IAMs can be found in Table 1.

Table 2 shows further detail on the transport modes modelled, mode shift and vehicle choice. Most IAMs model different transport modes, with amount of discrete modes modeled ranging from 3 to 14 modes. In DNE 21+, AIM-CGE, WITCH, and TIAM UCL the share of each mode is set exogenously, while IMAGE, MESSAGE, IMACLIM-R, POLES, REMIND and GCAM calculate these shares endogenously, based on cost and, in some models, time and saturation constraints. Vehicle technologies compete on the basis of costs, either through a logit distribution or least cost optimization. POLES takes exogenous assumptions on infrastructure development in to account as a constraint to vehicle choice. The parameters that are used to describe the costs of a transport technology as well as their future development differ per model. REMIND and WITCH, for example, assume that the investment cost for currently immature technologies (battery electric, hybrid, fuel cell) decrease endogenously following a global learning rate. In Imaclim-R learning rates are applied to all technologies. In other models costs of either immature or all technologies decrease exogenously in time.

Even though there are clear similarities across the models the formulations of projected service demand, representation of mode shift and vehicle choice, as well as the detail of transport options differ per model. Moreover, the consideration of modal speed, travel time and infrastructure constrains affecting demand varies and will impact projections.

	TIAM-UCL	IMAGE	Imaclim-R version 1	MESSAGE	POLES
System boundaries	The fuel mix is determined endogenously. Indirect fuel use from manufacturing, upstream energy and emissions are calculated but not tied to transport.	The model determines the fuel use, which is linked to the TIMER model, hence all emissions from fuels are considered. Embodied emissions of vehicles are included in the industry sector.	As a CGE model all GHG-emitting and energy producing/ consuming sectors are included. This implies that indirect energy use and emissions from fuel production and vehicle manufacture are included, but in the energy transformation and industry sectors.	All GHG-emitting and energy producing/ consuming sectors are included. This implies that indirect energy use and emissions from fuel production and vehicle manufacture are included, but the latter is not represented by a direct linkage.	The transportation sector covers the transport of goods and passengers. Transport of energy and associated losses, which are accounted for in the own energy uses of the energy sector.
Relationship drivers and demand	GDP, population, and GDPP drive the transport demand, where energy service demand grows slower than the underlying driver. The demand is influenced through a linear relationship with the drivers. Each transport demand in each region has its own relationship driver and demand coupling factor.	GDP, IVA (for freight) population, fuel price, non-energy price, load factor, mode preferences, energy efficiency, mode speed drive service demand per mode, on the basis of Travel money budget (TMB) and Travel time budget (TTB) formulation. A fleet module determines fleet composition within each mode, affecting mode cost, energy efficiency and fuel type for each mode.	The mobility demand and its modal split result endogenously from households utility maximization under constraints of revenues and time spent in transport. Each mode is characterized by a price and a speed. The price of cars mobility depends on fuel prices and the cost of car ownership. The price of other modes is determined in the general equilibrium framework by the intermediate consumption shares and prices. When the utilization of infrastructure reaches congestion, the marginal speed of the mode decreases, which limit its use.	Fuel prices, vehicle costs, GDP, population, vehicle speeds, vehicle occupancy rates, passenger vehicles per capita, annual distance traveled per vehicle, etc. Travel money budget, travel time budget, income, travel prices and travel speed determine service demand for the different modes (mode choice). The optimization framework determines the fleet composition within each mode. Freight service demand is drived by population, GDP and price elasticity.	Passengers: - Cars: income increase the number of cars per capita, fuel price affects the yearly mileage - Rail and buses: income increase the mobility, fuel price increase modal shift from cars to public transport Goods: GDP growth affects the mobility per mode

	REMIND 1.5	GCAM 3.1	AIM-CGE	DNE21+	WITCH	iPETS
System boundaries	Input of final energy in different forms is required together with investments and operation and maintenance payments into the distribution infrastructure as well as into the vehicle stock. Material needs and embodied energy are not considered.	The full fuel cycle of each fuel is represented. This includes biomass from an agriculture and land use model. No other upstream inputs to the sector are considered (e.g. vehicle manufacturing, roads)	Indirect energy use is treated in energy transformation sector	Indirect energy use is not included. For example, emissions from car manufacturing process is classified into the industrial sector.	Passenger LDV, Road Freight, Rail are considered while air and public transport) are embedded within a non-electric sector. Aspects such as infrastructure and the manufacturing of vehicles are incorporated into the overall GDP and representation of final goods.	All household expenditures on transport equipment, transport services (i.e. public transport, maintenance, etc) and transport fuels.
Relationship drivers and demand	GDP growth, the autonomous efficiency improvements, the elasticities of substitution between capital and energy and between stationary and transport energy forms. Mobility from the different modes is input to a CES function, the output of which is combined with stationary energy in a CES function to generate a generalized energy good, which	GDP, population, and services prices, derived from vehicle speeds and vehicle levelized average operating costs. GDP sets the scale of the demand, and determines the wage rate, which determines the opportunity cost of each travel mode. In this way, increases in GDP will increase the per-capita	Transport intermediate inputs and final demand. Passenger transport is determined by GDP with elasticity. Freight transport is determined by all industrial sectors inputs. They are formulated as multiplying input	Scenarios on service demand of road transportations are developed for passenger cars and buses separately based on per-capita GDP and the historical trends. As for road freight transport scenarios of cargo trucks, overall cargo service per-capita is estimated by the GDP	A linear Leontief function combines energy, O&M, vehicle capital and carbon costs to select the optimal mix of vehicle types. Vehicle ownership is a main driver which is set via a calibration based upon GDP growth per capita and the level of vehicle ownership per 1000 persons. Exogenous efficiency improvements are implemented within the model.	Household consumption of final goods (Coal, Electricity, Other Energy, Food, Transport, Other) is derived from income and (optimized) savings. Preferences for consumption goods are derived from underlying demographic structure changes (aggregated to a single representative

	is combined with labor and capital in the main production function for GDP.	demand for travel, and shift this demand towards the fastest modes.	coefficient	size, under assumption of modal shifts.		household) and change with income level.

Table 1: Drivers of energy demand in the transport sector of eleven IAMs.

Table 2: Technologies and final energy carriers

	TIAM-UCL	IMAGE	Imaclim-R	MESSAGE	POLES
Modes and vehicle types	Passenger : 7 modes (two wheel, three wheel international aviation, domestic aviation, road auto, road bus, rail), Freight: 7 modes (light, commercial, medium, heavy truck, rail, domestic navigation, international navigation), and hundreds of technologies.	Passenger: 7 modes (walk, bicycle, bus, train, car, high speed train and airplane), 6 freight modes (national ship freight, international ship freight, medium truck, heavy truck, rail freight, air freight) . Tens of technologies per mode.	Passenger: 4 modes (non motorized, personal vehicles, airplane, other) and 4 freight (trucks, freight rail, airplane, shipping). Technologies: ICE, efficient ICE, hybrid, plug-in hybrid and electric.	5 passenger modes and 1 freight mode. Other modes are not explicitly modeled but their energy use is accounted for via an exogenous energy demand trajectory. Tens of technologies options per mode.	Passengers: 7 modes (cars, motorbikes, bus, rail, air). Goods: 5 modes (heavy vehicles, light vehicles, rail, other (inland water), maritime). Technologies: ICE, plugin hybrid-electric, battery electric, fuel cell
Final energy carriers	Diesel, Gasoline, Ethanol, Electricity, LPG, Methanol, Natural Gas, Hydrogen, Fischer Tropsch biofuels.	The transport model only considers the secondary energy carriers: Hydrogen, Gas, Electricity, Oil, Biofuel	Liquid fuels from oil, Synthetic liquid fuels from other fossils Liquid fuels from biomass, Electricity	All fuels from the MESSAGE energy systems model are considered since the transport module	Oil products, Biofuels (energy crops and cellulosic feedstocks), Gas, Coal (for rail), Electricity and Hydrogen
Energy consumption of vehicles.	Share estimates split fuel consumption between road modes and rail modes. The model invests in technologies in order to satisfy the energy service demands in order to maximize consumer and producer surplus. Final energy consumption is endogenous to the model solution.	Different vehicle types with different energy efficiency's compete against each other (based on the multinomial logit), which allows for a change of energy efficiency of the mode.	For personal vehicles : explicit technologies with a efficiency characteristic and leaning on the cost. For other modes: efficiency improvement triggered by fuel prices.	Different vehicle types with different energy efficiencies compete against each other, which allows for a change of energy efficiency of the mode over time. The techno-economic parameters for each technology are exogenously assumed.	Unit consumption depends on: - price: long term elasticity to account for investment and short term to account for behaviour - income for behaviour, to control the spending on fuel for transportation (maximum "budgetary coefficient")
Determinants technology costs and shares	Investment costs, O&M costs, fixed costs – are based on exogenous assumptions and change over time in response to an exogenous learning curve. Vehicle market share is outcome of the model solution.	Net present costs based on literature, decreasing exogenously in time. We assumed that the technology costs is a global variable, as the technologies tend to be traded worldwide. Vehicle market share is based on a multinomial logit.	All technology characteristics are fixed in time, except costs that endogenously decrease with a learning rate. Vehicle market share is based on logit function.	The techno-economic parameters are exogenously assumed and change over time. There is also regional differentiation for certain technologies and parameter assumptions. Market shares are based on least cost optimization.	Road vehicles: Efficiency, lifetime, investment cost, fixed and variable O&M. These parameters change overtime exogenously. Vehicle competition based total user cost and infrastructure possible development.
Distribution between transport modes	Distribution is assumed exogenously, but the split between modes may slightly change due to responses to own price elasticities.	Time and costs are considered. Cost are weighted relative to time with a time-weight factor. The time-weight factor is determined by the travel money and travel time budget.	Households utility maximization under both constraints of revenues and time.	Time and costs are considered. Costs are weighted relative to time with a time-weight factor. The time-weight factor is determined by the travel money and travel time budget.	The different modes are mostly disconnected, limited by: differentiated elasticities to fuel prices and saturation effects (e.g. max. number of cars per capita, maximum air related mobility)

	REMIND 1.5	GCAM 3.1	DNE21+	AIM-CGE	WITCH	iPETs

Modes and vehicle types	Passenger: 4 modes, Freight: 1 mode. For passenger transport: LDV Aviation and Bus Electric Trains. For freight transport.	Passenger: 10 modes. Freight: 4 modes. Off-road vehicles, mining, or agriculture are not part of the transportation sector, except for China and India. ICE, electric, hybrid, fuel cell and compressed natural gas for bus/ passenger. For other modes two or one technology options.	Road transportation : 5 modes. The other subsectors are generated in a top-down manner. Technologies: ICEs, ICE efficienct, HEV, PHEV, electric, fuel-cell.	5 passenger modes (bus, train, car (incl 2- and 3-wheelers), train, airplane) Freight: 6 modes (national ship freight, international ship freight, medium truck, heavy truck, rail freight, air freight). Aggregated technology.	3 modes. Passenger (ICE, hybrid, plug-in hybrid and battery electric), Freight (Medium/Heavy vehicles with differing levels of electrification), Rail – passenger and freight (No vehicle types). Other transport modes are embedded within a non-electric sector.	
Final energy carriers	Liquids (Coal, Gas, Oil or Biomass (only second-generation with CCS for Coal and Biomass. Electricity (only LDV).Hydrogen (only LDV) (Coal, Gas or Biomass, all combined with CCS).	Liquid fuels (includes fuels derived from oil, coal, gas, and biomass), Electricity Natural gas (mostly natural gas; also includes biogas and coal gas),Hydrogen (from many fuels), Coal (for rail in China)	Gasoline, Diesel, Bioethanol and Biodiesel, CNG, Electricity, Hydrogen from coal, gas biomass and electricity Plus CTL (coal to liquid) and CTG (coal to gas).	Road: Oil, electricity, and biofuel (bus can use gas), Railway: electricity and coal, Ship: oil, biofuel and coal, Airplane; oil and biofuel.	Liquids can come from Oil or Biomass (traditional or second-generation). Gas is an option in Road Freight. Electricity can come from Coal, Gas, Oil, Biomass, Wind, PV, CSP, hydro or nuclear	Coal/biomass, Oil, Natural gas, Refined Fuels, Electricity
Energy consumption of vehicles.	The general efficiency of one transport mode improves exogenously over time in the CES function.	The energy quantity is derived from the average vehicle intensity and the load factor. The energy intensity of each technology is assumed to change over time exogenously. Endogenous changes of energy intensity are due to (a) switching from ICE to hybrid vehicles, (b) switching from smaller to larger vehicles, (c) modal shifting, or (d) switching to fuels with lower end-use energy intensity.	Energy consumption is determined based on the exogenous scenarios on service demand of road transportations in combination with technology (fuel efficiency of vehicles, costs and implicit discount rate) choice.	Multiplying coefficient. Fuel efficiency improvement is considered.	The efficiency of LDV and Road Freight transport modes improves exogenously over time based on selected efficiency improvement targets or selected forecasts.	
Determinants technology costs and shares	Efficiency, lifetime, investment cost, fixed O&M. Investment cost for battery electric and fuel cell vehicles decrease endogenously following a global learning rate towards a given floor cost. The distribution of LDV vehicles follow cost optimization with different non-linear constraints	Capital costs are amortized over an exogenous lifetime, assuming a 10% discount rate. Non-fuel operating costs include insurance, registration, taxes and fees, and standard O&M expenses. These can decrease exogenously for immature technologies such as electric cars or hybrid vehicles. . Vehicle market share is based on logit function.	Fuel efficiency of vehicles and costs are assumed to be improved exogenously. Lifetime does not change over time. Market shares are based on least cost optimization	Not explicitly determined.	Efficiency, lifetime, investment cost, fixed O&M. Investment cost for battery electric and fuel cell vehicles decrease endogenously following a global learning rate towards a given floor cost. The distribution of LDV vehicles follow cost optimization with different non-linear constraints	
Distribution between transport modes	The distribution between LDV and other modes is determined via the CES production function, driven by the elasticity of substitution (1.5) and the evolution of the efficiency	The modes compete using a logit share formulation, where the costs includes both the vehicle cost and the time value cost. The time value cost is derived as the wage rate divided by the average transit speed, and modified by an exogenous time-value	Travel demand is exogenously given for each mode. Modal shift is not endogenously		The distribution between modes is fixed and determined via separate demand calculations.	

	parameters.	multiplier that is generally close to 1.	evaluated.

1.3. Transport sector model development

The ADVANCE IAM modelling teams indicated during the project that there are a few priority areas for transport model improvement. A summarized overview of the main model developments are discussed below:

- Technology development:

There is a high uncertainty in vehicle technology cost and efficiency development. This is illustrated for example by the more rapid decrease of battery cost used in electric vehicles than previously projected by the literature (Nykvist & Nilsson, 2015). Modelling transport technology characteristics such as costs and efficiency explicitly, using state of the art data on current and future performance can improve model projections. Relating costs through learning curves to vehicle deployment can improve the modelling of cost dynamics.

> With a detailed representation of costs and efficiency the impact of fuel and or technology subsidy and taxes on vehicle choice can be modelled. Moreover policy measures such as efficiency standards and technology regulation can be assessed.

- Mode choice/shift:

Transport modal shares differs per region, time period, and depends on the costs of mode travel, its speed, its comfort level, and individual preferences and possibilties, such as income. Historically there has been a shift toward faster modes in time but also with rising GDP. Modelling transport mode shift dynamics, in agreement with historical observations, is an improvement that some IAMs wanted to make.

> This would give the opportunity to assess policies addressing modal shift towards low carbon intensity modes such as public transport, walking and cycling.

- Infrastructure capacity and costs:

The representation of transport infrastructure development, and in particular its costs, is in most IAMs not accounted for and can be improved. This would be useful to assess more precisely the infrastructure policies and their macroeconomic effects. Infrastructure development at the same time also impacts modal choices, which is constrained by infrastructure capacities (with potential congestion). This model development exercise is part of ADVANCE task 5.4.

> By modelling infrastructure development explicitly the costs of transport infrastructure policies can be assessed

- Heterogeneity consumer choices and behavior

The adoption to new vehicle technologies will depend on choices made by consumers. Apart from travel costs there are other factors that influence choices made, that can be described as behavior. Capturing behavior aspects of decision making as well as heterogeneity could improve the representation of technology transition in the models. This model development exercise is part of ADVANCE task 3.1.

> By considering behavioral considerations transition to advanced vehicles possibly is more difficult to decarbonize the transport sector. This will allow us to explicitly analyze policies related to transition to new technologies by removing these barriers to market adoption (e.g., like cities installing EV chargers throughout urban areas).

- Historical data and regional base year calibration

Transport data in the form of kms travelled worldwide and over time, split per mode, as well as technology characteristics, such as efficiency and costs is very valuable. Calibrating the IAMs to these type of datasets would improve base year model outcomes as well understanding current trends.

Calibration of the model will improve near term policy assessment of current and planned policy at the regional level.

Five IAM transport models have been working on transport model development within the ADVANCE project, focusing on the first three main topics. In the next paragraphs the model development will be described in more detail. As part of ADVANCE historical regional base year data per passenger mode published by the International transport forum, and two individual studies have been compared. For more information and access to the base year datasets collected and compared contact Oreane Edelenbosch (oreane.edelenbosch@pbl.nl).

1.3.1. GEM-E3 Transport model development

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Motivation of the work and policy relevancy

The GEM-E3 model has been further developed in the ADVANCE project with the aim to represent in detail the transport sector. In the standard version of the model fuels and transport technologies were represented in a rather aggregated form. Higher resolution of the transport sector increases model flexibility, realism and applicability so as to adequately represent and adjust to transport specific and ambitious emission reduction policies. In methodological terms, MCP formulation of the transport module has increased the computational efficiency of the model.

Data/Modelling method

Transport-rich GEM-E3T model is calibrated to GTAP. GTAP data on land transport, are disaggregated into: road passenger/freight and rail passenger/freight transport. Water transport is divided in passenger/freight transport. For this, statistics from Eurostat, the OECD and PRIMES-TREMOVE databases on transport sector revenues, activity per transport mode and purpose of transport, bilateral trade volumes and transport margins have been used. The model considers a stock of vehicles inherited from previous periods, using PRIMES-TREMOVE scrapping rates, and it determines endogenously the utilization rate of existing vehicles based on operational costs. GEM-E3T distinguishes between conventional vehicles, plug-in hybrid vehicles and advanced vehicles (e.g. battery electric vehicles). The shares of technologies in the vehicle fleet are determined using discrete choice models, which follow a Weibull functional form, based on the fixed and variable costs of the options.

The model uses Constant Elasticity of Substitution (CES) functions with a nested separability scheme. Firms decide between capital, labour, energy and transport and materials at the top level of the production decision tree. Demand for transport is divided into freight transport and business trips of firms' employees and overall transport demand is distributed between these two categories in fixed proportions. Freight transport category is disaggregated into land and water freight transportation. In the lowest nest, demand for land transport is allocated between road and rail transport. Regarding transportation of firm's employees, the model considers air, land and water transport with a similar structure of the decision problem to that of freight transport with the addition of aviation. Households allocate their mobility between private and public transport. When choosing public transport means, households are price takers and pay a ticket fare. If households' choose to self-supply the services, they face an average cost reflecting both fixed costs (cost of purchasing a vehicle) and variable costs associated to vehicle operation (e.g. fuel cost). Substitution (imperfect) is possible between public and private transport means based on relative prices.

Table 3: Detail of transport representation in GEM-E3

Features	Old GEM-E3 Version	ADVANCE GEM-E3T version
Sectors	Transport services, Air-Land-Water	Air, Road-Freight, Road-Passenger, Rail-Freight, Rail-Passenger, Water-Freight, Water-Passenger, Production of Electric Vehicles
Vehicles	Representative	Pure Conventional, Conventional hybrid, Conventional with biofuels, Plug in hybrid, Pure electric
Fuels	Coal, Oil, Gas, Electricity	Coal, Oil, Gas, Electricity, Biodiesel, Ethanol

New modelling results

GEM-E3T provides an enhanced bottom-up representation of the transport system. The model captures changes in vehicle stock which occur as a result of the increased demand of mobility and of cost differentials (e.g. through innovation that reduce the cost of batteries) that change the relative price of the various types of vehicles. This feature allows capturing the effect of policies that focus on the penetration of cleaner vehicles (e.g. development of recharging infrastructure, tighter CO_2

standards etc.). The model represents explicitly the production of biofuels. A sector producing electric vehicles has been added in the model and it captures price differentials that occur from the different production chains per vehicle technology. The nested functional form of the model approach allows direct links with the PRIMES-TREMOVE transport categories and it provides the necessary flexibility to use different values for the elasticity of substitution at each nest so as to capture substitutability effects between alternative transport options. Model results are obtained per transport mode (air, land, water), technology (conventional, electric, hybrid vehicles) and purpose (passenger, freight). The new model version has been tested with alternative scenario simulations including the impact of transport regulations and the penetration of electric vehicles on CO_2 emissions and the economy of EU28. It has been found that a deployment of electric vehicles in 2050 by 70% and biofuels by 34% in the EU28 mix would reduce GHG emissions by 60% in the transport sector for a cumulative cost of 0.1% in terms of GDP over the period 2020-2050.

Concluding Remarks

The development of the transport module of the GEM-E3 model allows to:

i) improve its flexibility and realism in adjusting to stringent GHG emission reduction constraints
ii) to perform simulations regarding detailed standards of the transport industry

Data requirements are quite intense to expand the transport sector within an input output framework. In modelling terms the implementation is not very demanding as it follows the basic MCP formulation already established in the model. An element that requires further improvement regards the accumulation of vehicle stock and the optimum computation of the scrapping rate in a recursive dynamic framework.

1.3.2. Modelling Transport Infrastructure in the IMACLIM-R Global E3 model

Author: Eoin O Broin (Centre-CIRED)

Motivation of the work and policy relevancy

As part of WP5.4 of the ADVANCE project, the modelling of transport infrastructure in the IMACLIM-R Global E3 Model has been improved. The model includes three transport modes (air, public, road) in 12 global regions .The improvements to the model have involved three components; (i) detailed modelling of how road infrastructure for automobiles is deployed, (ii) the inclusion of costs for the deployment of transport infrastructure for automobiles, public transport and air transport, (iii) the inclusion of process emissions so as to quantify the embodied emissions in the deployed infrastructure. The motivation for the work has been to improve the robustness of the model by including costs and process emissions, and to also explore possible macroeconomic effects. Given the importance of infrastructure in greenhouse gas mitigation strategies, the improvements to the model can allow policy scenarios with restricted or enhanced transport infrastructure roll-out to be considered as well as standard carbon price scenarios.

Data/modelling method

Heretofore in the IMACLIM-R Global E3 Model, infrastructure for automobiles has been deployed subject to the annual increase in passenger kilometers (pkm) travelled. In the new version of the model two parameters are considered as main drivers of this deployment: the target infrastructure utilization rate and the annual change in the stock of vehicles (linked to changes in personal income). For the first parameter, a goal of 50% road utilization rate per region is set but constrained to improve (i.e. approach 50%) by a maximum of 2% per year. This constraint is to prevent the model constructing unrealistic amounts of road infrastructure in any one year e.g. for Brazil which currently has a road utilization rate of over 80% i.e. a high level of road congestion. The result of the combination of the increase in the stock of vehicles and target utilization rate dictates the annual increase in road infrastructure construction. This result is then compared against : (i) The construction industry capacity in the region, (ii) The density of the existing road network, and (iii) the maximum percentage of GDP that can go to infrastructure. These are three checks on the amount of new road infrastructure that the model estimates. The latter check is set at 2% and includes costs for construction of new roads and operation and maintenance (O&M) of the existing road network. The method used for the deployment of infrastructure for public transport and airports has not been changed in the new version of the model, however the costs of their deployment have been included. Calibration of the new model has found that pkm/capita increases with income and that increased income/capita leads to mode switching to faster transport modes, as (Schäfer, 2007) has shown empirically.

The above described methodology for updating the length and cost of road infrastructure is based on an approach carried out by (Dulac, 2013)for the IEA. The author has also carried out an extensive survey to establish average costs for road, and rail construction, upgrade and O&M for various World regions. Dulac's costs are used in this work to provide calibration values for the cost of infrastructure for the model calibration year, 2001. Costs for road infrastructure are made up of new roads and parking spaces, upgrade of existing roads and O&M for existing roads and parking spaces. Costs for construction and O&M of Air infrastructure (airports) are estimated independently using data from the (OECD, 2015) and other sources.

New modelling results

BASELINE: **Key Message – baseline gets changed when transport infrastructure costs are added to model.** Investments in infrastructure increase activity of the construction sector and this slows structural change of the economy towards more productive and less carbon intensive sectors. This results in lowered GDP and higher intensity. Process emissions from cement have been added to the model as well thus increasing total CO_2. Direct emissions from transport increase as well because of a large increase in public transport and air travel mobility (pkm). This is a rebound effect. Lower GDP lowers demand for oil and oil prices and given that energy is a small part of costs of public transport and air travel these two modes increase in response to the cheaper oil.

GENERAL RESULTS: **Key message – restricting infrastructure lowers cost of meeting CO_2 goals**. Embodied CO_2 emissions in transport Infrastructure are not significant(<1% of total CO_2 emissions). This is because most emissions from cement production are embodied in the building sector. In a low carbon scenario however their proportion increases because mitigation mostly occurs in other sectors and there is continued roll-out of infrastructure. The cost of mitigation is lower in a scenario with a carbon budget plus a restriction on infrastructure expansion of road and airports, than in a scenario with just a carbon budget. This is connected to restricted infrastructure for road and air being compensated for by increased public transport and other economic activities that result in less carbon intensive activities which also result in less use of oil and coal (natural gas increases). The rebound in demand for public transport and air travel which occurs in the baseline also occurs in the restricted CO_2 scenario.

1.3.3. Transport sector model development in MESSAGE

David McCollum – International Institute for Applied System Analysis (IIASA)

Motivation of the work and policy relevancy

Representations of the social, technological and physical systems in global IAMs are necessarily stylized and simplified. Yet, these models are increasingly being designed to be more 'realistic' by incorporating features observed in the real world. An improved representation of human behavior is at the frontier of research for IAMs, particularly in the area of non-monetary preferences of heterogeneous energy consumers and technology adopters. Capturing these behavioural features increases the usefulness of IAMs to policy makers by allowing the models to (more realistically) assess a wider suite of policies than before (i.e., not only price-based policies). This is particularly important in light of the fact that real-world climate policies are often implemented via instruments other than carbon pricing; in fact, many make use of a mix of instruments.

Data/modelling method

Work carried out at IIASA within the context of the ADVANCE project has led to the incorporation of behavioural features relevant to vehicle choice into the MESSAGE-Transport IAM framework. The original objective was to develop a bridging approach between detailed vehicle-choice models and more aggregated global IAM frameworks. More specifically, the approach disaggregates light-duty vehicle demands into a mix of consumer groups and then assigns additional cost terms ('disutility costs') to the vehicle technologies within each of these groups, in order to capture non-cost barriers to alternative fuel vehicle adoption. In one formulation, for instance, consumers are divided up along three separate dimensions, each with three distinct consumer types (for a total of 27 groups): (i) Settlement pattern (Urban / Suburban / Rural); (ii) Attitude toward technology adoption (Early Adopter / Early Majority / Late Majority); (iii) Vehicle usage intensity (Modest Driver / Average Driver / Frequent Driver). Region-specific disutility costs are estimated using the MA^3T vehicle-choice model of Oak Ridge National Laboratory.

New modelling results

Several insights emerge from the scenarios that employ our new approach for capturing non-monetary considerations in the transport sector. We find representing heterogeneity and behavior significantly alters the model-estimated portfolio of light-duty vehicles deployed over the coming decades to meet climate mitigation targets: the timing of electric vehicle penetration is delayed by up to several decades, and hydrogen and natural gas use decrease significantly. Because mitigating LDV CO_2 emissions becomes marginally more expensive from the perspective of the model, the scenarios combining heterogeneity and behavioral considerations see a much greater quantity of cumulative (direct) CO_2 emissions from LDVs out to 2100 (i.e., less CO_2 abatement), for a given carbon price. A key conclusion of the research is that non-price-based policies targeting the deployment hurdles for alternative fuel vehicles (AFVs) could counteract the reduced effectiveness of price-based incentives, particularly in the early-market phase of AFVs. Examples include vehicle or fuel emissions standards, mandates and subsidies, and refueling/recharging infrastructure support. These are potential future directions for modeling.

Concluding Remarks

The model formulation developed within ADVANCE is flexible and simple enough to be applied to a diverse array of IAMs, yet is detailed enough to capture the most influential behavioral features that have previously been identified in the empirical evidence base. There are areas where the modeling could be improved, however. For instance, a recognized bottleneck for behavioral modeling is the lack of existing empirical data packaged in a form that is amenable to global modeling and analysis. The empirical research community – in particular the social sciences – has an important role to play here. Through advances in both theoretical and applied research, the major behavioural features driving future energy consumption patterns can be better understood.

1.3.4. AIM/CGE Transport model development

Author: Shinichiro Fujimori - National Institute for Environmental Studies (NIES)

Motivation of the work and policy relevancy

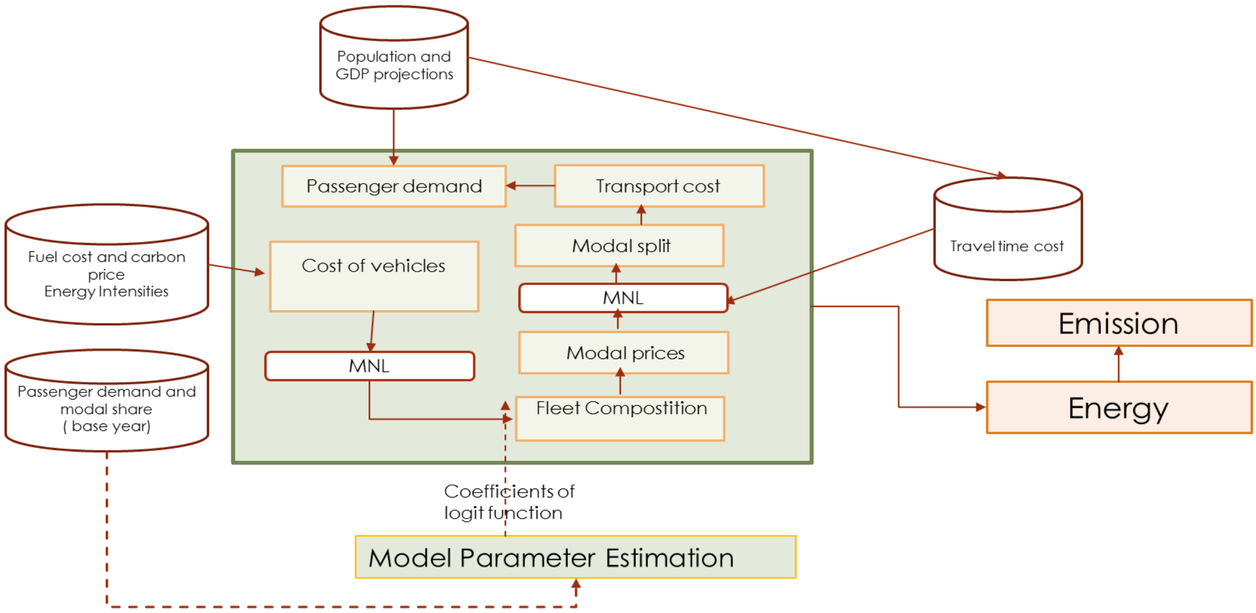
In the present AIM/CGE model, the transport sector is represented at a highly aggregated level and travel time cost has not taken into consideration. In this exercise, we refined the representation of the transport modes as well as included the travel time cost. In the new transport module, the modal shift between the private and public mode is allowed endogenously. Impact of the policies like carbon tax, energy tax or subsidies, fuel economy standards, tax based on the car size as well as building dedicated corridors for railways and buses on the travel demand and modal structure can be assessed using this new transport module.

Data/modelling method

New transport module is soft-linked with the AIM-CGE model. The fuel price, carbon price, GDP and population are taken from the AIM CGE model and inputted into the transport module. This global transport demand is calculated endogenously using fixed income and price elasticity estimated using the historical cross sectional data as mentioned in the below equation.

$$Passenger\ transport\ demand_{r,t} = \frac{GDP_{r,t}}{POP_{r,t}}^{\alpha} * Price^{\beta} * Population_{r,t}$$

Mode, vehicle size and technology is selected using the logit function based on their cost. The structure of the new transport module can be seen in the below figure.



Concluding remarks

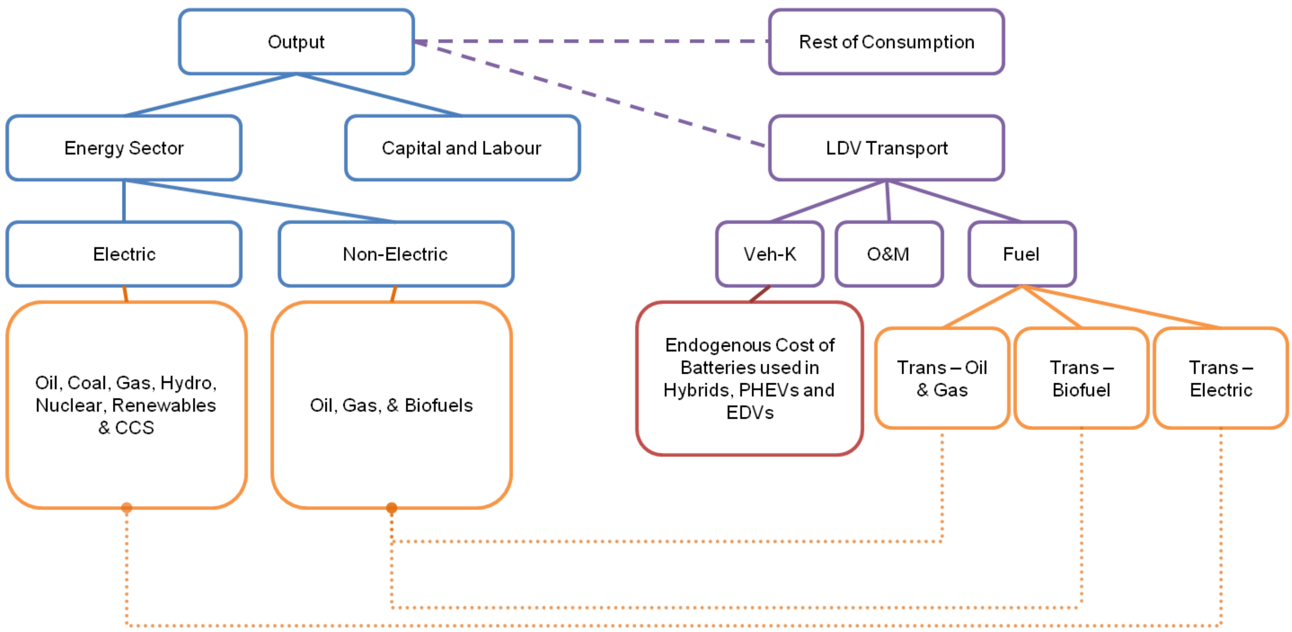
Non-motorized modes like bicycle and walking as well as non-physical travel like ICT, online shopping is also required to be considered in the model. Further work is required to assess the effect of land constraints, congestion and infrastructure investment on the travel demand and modal structure.

1.3.5. FEEM Transport model development

Samuel Carrara - Fondazione Eni Enrico Mattei (FEEM)

The figure below shows how the structure of the Light-Duty Vehicles (LDV) transport sector fits and interacts with the supply side CES (Constant Elasticity of Substitution) framework in WITCH. The vehicle fleet (denoted in the figure as Veh-K, and featuring traditional cars, hybrid, plug-in hybrid and battery electric vehicles) is determined via a Leontief function of a range of different costs, which comprise the vehicle cost (including battery cost), O&M costs, fuel costs and any associated carbon costs based on the fuel mix within the sector. Fuels (oil, traditional biofuels and advanced biofuels) and electricity are sourced from the energy sector. Investments in the transport sector are accounted for when calculating the aggregate consumption of the macroeconomic model(Bosetti, 2013; Longden, 2014).

Figure 1



The number of vehicles is set equal to an exogenous projection and is computed before the model iterates through the Nash loop. The calculation of vehicles has been sourced from the IEA/SMP model which is in turn based on the work of (Dargay, 1999). Fuel consumption and service demand are calculated starting from travel intensity, again basing on the IEA/SMP model (Fulton, 2004). The model optimizes the fleet composition and the fuel portfolio.

A considerable modeling improvement has been carried out in the context of the ADVANCE project – WP2. In particular two main points have been addressed.

1. At the beginning of the project, WITCH featured the modeling of the road passenger sector only, and specifically of LDVs. An important issue which affected the model was the low or null penetration of Battery Electric Vehicle, due to the excessive capital costs fixed in the model, which were eventually re-aligned with the other models' ones during the project. This aspect is particularly relevant in WITCH, since the model features endogenous technical change: the cost of electric batteries, on which the cost of electric vehicles (hybrid, plug-in hybrid and battery) mainly depends, decreases over time thanks to dedicated R&D investments. Initial values and calibration parameters were thus revised, significantly affecting the results. Unsurprisingly, the outcome has been a higher penetration of electric vehicles. Other minor parameters were also recalibrated basing on the data shared within the work package.

2. LDVs represent by far the largest share of the road passenger sector, and they represented averagely about 50% of the overall final energy of the transport sector in 2005 across models. In order to progressively complete the modeling of transportation and explore a new dimension in this sector, a road freight module was added to WITCH in the past months (road freight represented almost 30% of transport final energy in 2005), following the same modeling framework as the LDV module described above.

Future work will be oriented in two directions, which could be defined as “quantitative” and “qualitative”. Concerning the first, the model will be enriched by the addition of new transport sub-sectors, starting from rail passenger and rail freight and by the addition of new transport solutions within the road passenger sector (i.e. public transport – e.g. buses – and 2W&3W’s). Concerning the second, the model will be improved by implementing modeling solutions to describe consumer behavior and choices, and to allow for modal shifts.

1.4. Transport model comparison[1]

1.4.1. Introduction

The transport sector GHG emission projections of eleven ADVANCE IAMs transport models are assessed and compared, by analyzing the underlying projection of components (e.g. fuel use, energy efficiency, modal shares and activity growth) by the models that together compose the total GHG emissions and energy use projections. The aim is to understand how the projections are build up, how the models compare to each other and possibly identify whether model improvement can be made.

The International Energy Studies (IES) group at the Lawrence Berkeley Laboratory (LBL) have performed multiple studies to assess the general trends in CO_2 emissions development historically originating from the transport sector in different regions and over different periods of time. In their comparative analysis they decompose the developments in total CO_2 emissions in to the contributions changes in population, transport activity, structure, energy efficiency and CO_2 intensity, in a kaya identity type of formulation (Schipper, Howarth, & Carlassare, 1992; Scholl, Schipper, & Kiang, 1996). This methods allows to identify the role of the underlying processes. In the equation below it can be seen how these components relate to the total emissions.

Equation 1

$$Transport\ CO_2\ emissions = \sum_{Mode} population * Activity * Modal\ share_{Mode} * Energy\ efficiency_{Mode} * Fuel\ mix_{Mode}$$

The formula shows how the total CO_2 emissions from the transport sector depend on the amount of people (Population); the average distance travelled (Activity); the share of the different transport modes in fulfilling this travel demand (Modal share); the energy used per passenger km travelled for each mode (Energy efficiency); and the CO_2 emissions per unit of energy consumed (Fuel mix). The last two components combined, essentially the CO_2 emissions per passenger km, is the CO_2 intensity per mode. Changes in these components are not necessarily independent from each other, for example an increase in fuel prices can for example lead to change of mode share as well as decrease in travel activity. It does however give a measure of relative importance of the change of each of the components in the development of CO_2 emissions.

The IES group used this approach to compare developments in energy use and CO_2 emissions in amongst other regions USA, Japan, France, former West Germany, Italy, UK, Denmark, Norway and Sweden, over the period 1973-92. They found that activity growth is the main contributor to the increase in CO_2 emissions in these regions. On average in the OECD countries the activities grew with 37% in 1992 with respect to 1973. In most countries the modal structure shifted from bus and rail to automobiles and airplanes. The increase of car ownership in this period, driven by growth in income, expanding suburbs, and more women participating in the workplace, led to an increase in activity. Higher income along with decreasing cost of flying led the larger share of air travel. The change in CO_2 emissions as a result of the mode shifts were however relatively small compared the contribution of activity growth(Scholl et al., 1996).

In the period analyzed, the changing CO_2 intensity per mode led to some unexpected results. In Japan for example the share of air travel increased, while its CO_2 intensity decreased eventually becoming less CO_2 intensive than travelling by car. The shift to air transport therefore resulted in a decrease in total CO_2 emissions. This example illustrates the relevancy and ype of analysis that can be performed

[1] This section is planned to be submitted to the special issue “Transport in IAMs” in the journal Transportation Research Part D: Transport and Environment.

through the decomposition method. CO_2 intensity changes historically were mainly due changing energy efficiency, while the fuel mix remained fairly constant. In all countries modal shift resulted in an increase of emissions.

To compare the IAM transport models future CO_2 emissions projections, the methodology described is used, aiming to identify for each model the underlying trends that lead to transport CO_2 emissions projections in both a baseline scenario as well as a mitigation scenario.

1.4.2. Method

Eleven IAMs have participated in the exercise, namely AIM/CGE, DNE21+, GCAM, GEM-E3, Imaclim-R, IMAGE, POLES, MESSAGE, REMIND, TIAM-UCL and WITCH. The model structure has been described in Section 1.2. In this comparison study the focus is on the passenger transport but the same approach is planned to take place for the freight sector. In Table 4 the policy taken in to account in the baseline are described, as well as the passenger transport modes explicitly modelled.

Table 4 Transport baseline policy and mode representation in IAMS.

	AIM/CGE	**DNE21+**	**GCAM**	**GEM-E3**	**IMACLIM V1.1**
Baseline policy	no explicit policy	Extrapolating current trends	USA café standards		no explicit policy
Modes	Train, Aviation, Bus, LDV	LDV, Bus	LDV, Bus, 2W&3W, Aviation, Train	LDV, Aviation, Train	LDV, Bus
IMAGE	**POLES**	**MESSAGE**	**REMIND**	**TIAM-UCL**	**WITCH**
Extrapolating current trends	no explicit policy	Extrapolating current trends	Current taxes, and extrapolating		Extrapolating current trends
LDV, Bus, Train, Aviation	LDV, Bus Aviation, Train	LDV, Bus, 2W&3W, Aviation, Train	LDV	LDV, Bus, 2W&3W, Train	LDV

Two scenarios have been compared:

- Baseline scenario
- Mitigation scenario aiming at a stabilization level at 450 ppm CO_2-eq

The baseline is the standard run scenario of the IAMs. No attempts have been done to harmonize assumptions. In the table above the transport baseline policy included in the scenarios can be found. The main model drivers GDP and Population can be found in Figure 2.

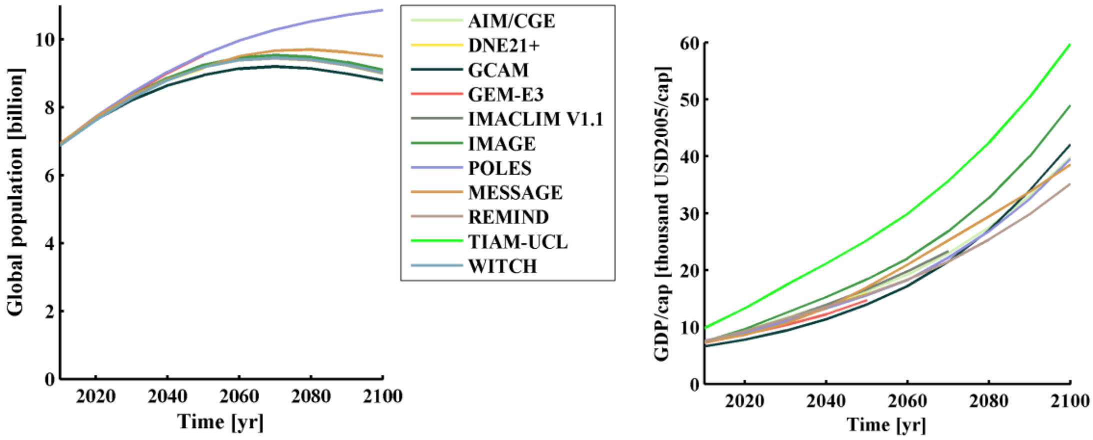


Figure 2 Scenario drivers: a) Global Population b) Global GDP MER per capita

1.4.3. Results

In Figure 3 the direct passenger transport emissions[2] projected by the eleven IAMs are shown in the baseline and mitigation scenario. The models show a strong increase of emissions. In 2100 a large range in total emissions is visible in the baseline (from 2-12 Gt/yr) and the depict different pathways, either continuous increase until 2100, saturation, or even a decrease in annual emissions. In the mitigation scenario all models show a strong decrease in transport emissions compared to baseline, necessary to achieve the climate target. A few model show a gradual decline in emissions after 2020 while other reduce emissions more rapidly after 2050.

Figure 3 Transport direct CO2 emissions projected by IAMs in baseline (left) and mitigation scenario (right).

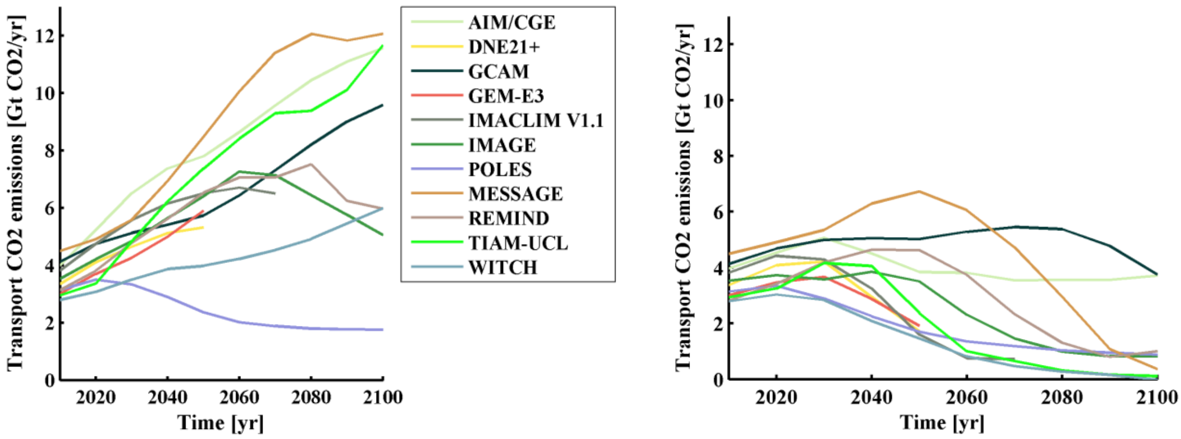


Figure 4 shows the effect of the development a single component (Activity (pkm), Structure and CO_2 intensity (CO_2/pkm) on CO_2 emissions, under the assumption that the other components remain at their 2010 values for both scenarios. In the baseline scenario the models the structure and CO2 intensity component development is similar across model, while there is a high uncertainty in activity development, which explains the differences in baseline CO_2 emissions pathways. TIAM-UCL, AIM/CGE and MESSAGE with high activity growth assumption project high emissions. GCAM does show some structural effect towards carbon intensive modes, which explains why even with relatively low activity growth the projected emissions are on the higher end of the range. POLES relative low transport emissions on the other hand can be explained by the strong decrease in CO2 intensity and structure effects. In the mitigation scenario CO_2 emission decrease is largely being achieved by lower CO_2 intensity, and for some model activity decrease (ranging from 0-20%

[2] The Passenger projections of REMIND and WITCH only account for LDV transportation. REMIND includes indirect emissions in the CO_2 emissions reported.

decrease) while mode shifting plays a less important role in achieving a GHG emission target. The CO_2 intensity reduction pace throughout the century is uncertain across the models in the mitigation scenario, playing in important role in the sectors mitigation potential.

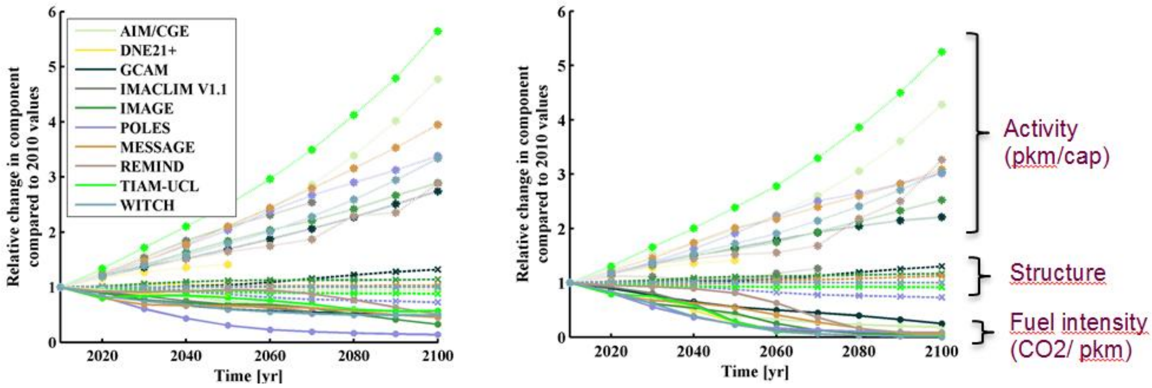
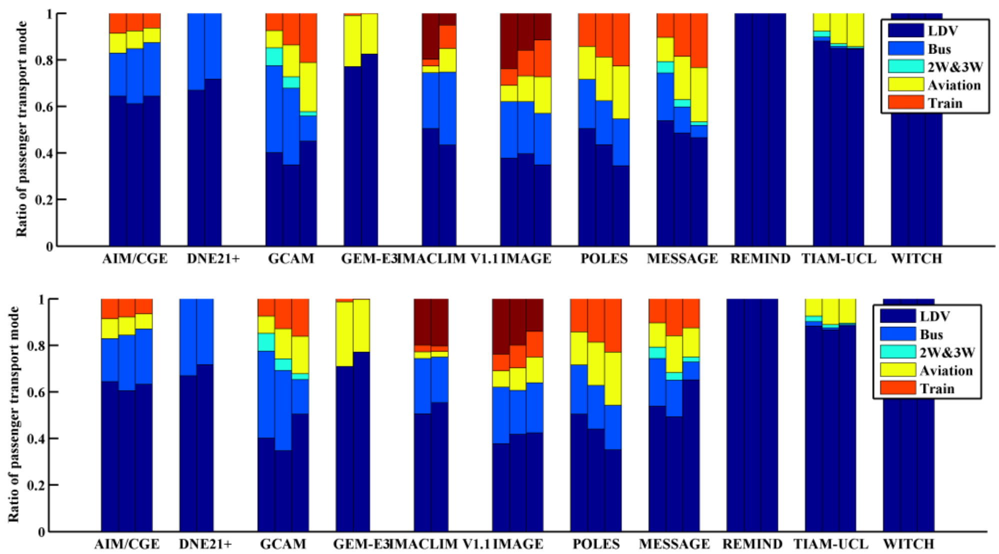


Figure 4 Passenger transport component development following Equation 1.

Diving one step deeper in the model comparison, Figure 5 shows modal shares in 2010, 2050 and 2100. Different modes have been explicitly accounted for in the transport models (Table 4). REMIND and WITCH only model LDV explicitly as passenger mode. For that reason structural change, as defined in this comparison, doesn't play a role in these models projections. In MESSAGE, IMAGE, GCAM and Imaclim-R speed affects modal choice, which in all four models leads to a shift towards aviation. TIAM-UCL, and POLES also show increased aviation shares. However in the POLES projection bus and train increases as well resulting in decreasing emissions due to structural change. Varying definition of modes modelled can partially explain different base year data shares. In all models distribution of modes is hardly changes in response to climate policy, and is therefore plays a limited effect as a measure to decrease emissions.

Figure 5[1] Passenger modal shares (structure component) in 2010, 2050 and 2100 for baseline (top) and mitigation scenario (bottom).



[1]GEM-E3 structure figure is based on final energy use per mode and not pkm, where aviation is total aviation (also for freight), and LDV is total passenger road transport (incl. bus and 2W &3W).

In the figures below the CO_2 intensity change is plotted against the activity growth, where the top figures show the total passenger transport and the bottom are specified for LDV vehicles. Also in these figures for all models but REMIND, only direct transport emissions are accounted for. Most models show a decrease in passenger transport CO_2 intensity in the first decades, following with more constant CO_2/pkm value in the second half of the century. LDV specific CO_2 intensity reduction is more uncertain across the models. Transport activity continues to grow throughout the models, resulting for some models to higher CO_2/ per capita values in 2100, indicated by the size of the bubbles. In the mitigation scenario a strong reduction of the CO_2 intensity reduces the CO_2/cap values in all models, and in some models activity is reduced in response to the implemented climate policy.

A similar quadrant is shown in

Figure 7, showing the fuel mix compared to the energy efficiency. The results show that in a baseline scenario in most models the reduction of CO_2 intensity is the result of energy efficiency increase, although IMAGE and POLES also show Fuel intensity reduction between 2050-2100. In the mitigation scenario further CO_2 intensity reduction is the combined effect of fuel switching and energy efficiency measures. It should be noted however that electric vehicles use are more efficient than ICE, and therefore switching to alternative compulsion mechanisms could lead to both effects

Figure 6 Passenger transport activity compared to CO2 intensity development over time for total transport (top), cars (bottom), baseline (left) and mitigation scenario (right).

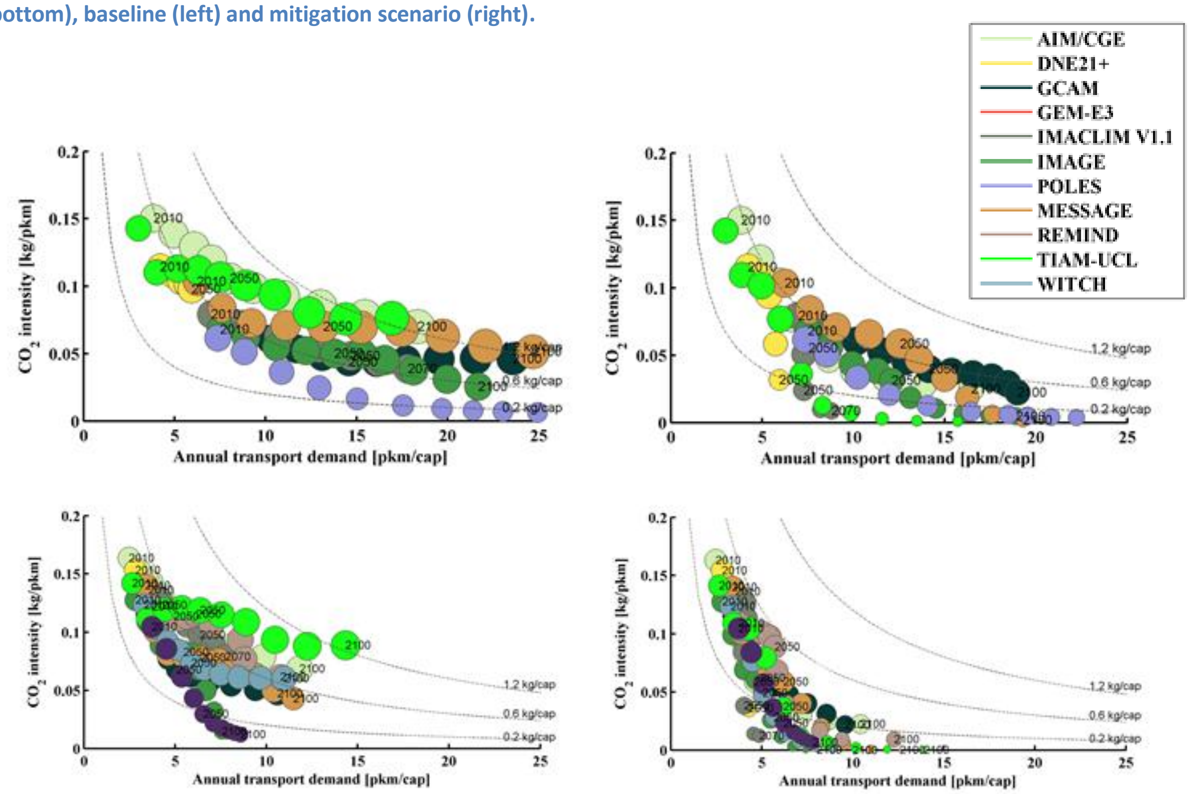
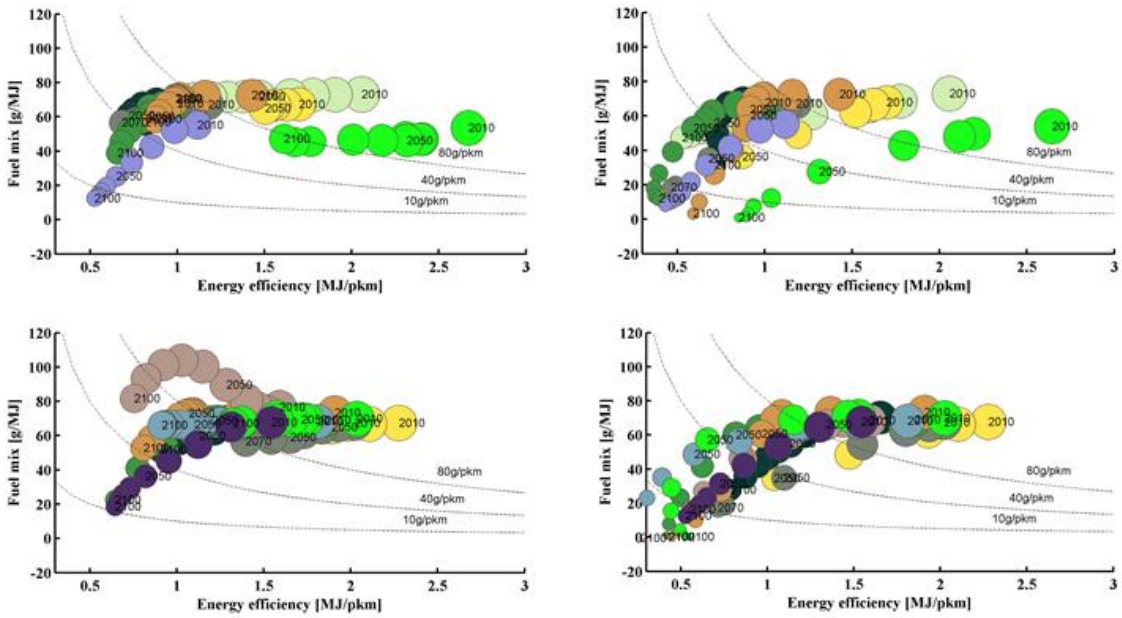
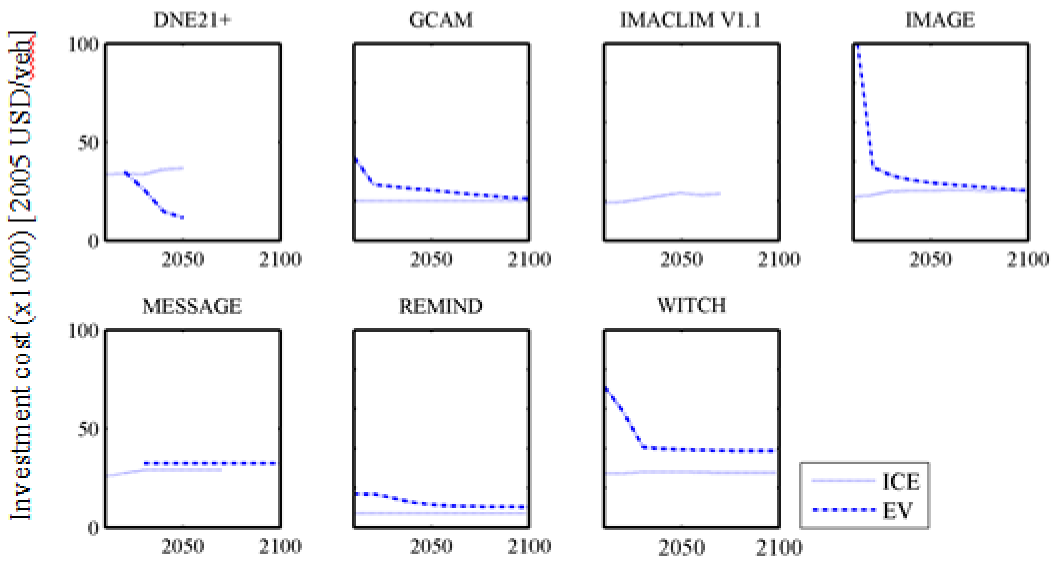


Figure 7 Passenger transport energy intensity compared to Fuel intensity development over time for total transport (top), cars (bottom), baseline (left) and mitigation scenario (right).



Finally, in attempt to explain different LDV fuel mix and energy intensity pathways, a closer look in to vehicle input is made. In Figure 8 the efficiency and investment cost over time are presented for electric vehicles (EV) and convention internal combustion engine (ICE) vehicles. The development of EV cost are projected to decrease rapidly in the coming 20 years. However whether the EV vehicle price approaches the ICE price is uncertain across the models, which will impact fuel switching response to a carbon tax. WITCH for example shows a relatively large difference in vehicle price between the technologies, and also less decrease of fuel mix in their scenarios. However it should be noted that we have only assessed EV prices, while Fuel cell vehicles or using biofuel can also impact the fuel mix.

Figure 8 Investment cost of EV and ICE over time in IAMs



Figur
e 9

1.4.4. Conclusion and discussion

IAM transport projections have been compared by decomposing the scenarios in to development of certain sub-component: Activity, Structure, Energy intensity and Fuel mix. Based on the analysis we conclude that in these scenarios CO_2 mitigation occurs mainly as a result of energy efficiency and changing fuel mix, and for some models activity decrease. Changing the modal structure to less CO2 intensive modes is not applied as measure to decrease emissions. In baseline and mitigation scenario there is variation across the models on activity growth as well as fuel switching, which could possibly be explained by different input assumption on investment cost and technology efficiency. Relating inputs to model outcomes could help clarify model differences and pinpointing the uncertainties (such as technology development) that result in this range.

1.5. Price and income elasticity set up[3]

1.5.1. Motivation and scope

This study is an attempt to compare changes in future energy transport demand in different models by means of income and price elasticities. These elasticities indicate the degree of responsiveness of energy demand to change in prices or income, and are often derived from empirical econometric research, based on historical data. The detailed information gathered in WP2 and WP3 can also be represented in the form of price elasticities, influenced by behavioral aspects and the availability of demand-side technologies and their costs. Building upon the improved and extended demand-side models of WP2 and WP3 in this work the price-responsiveness of energy demand will be explored. The results will be confronted with empirical evidence on the elasticity of energy demand to price, income and policy shocks. This will allow us to compare and contrast the modeling and empirical evidence of issues such as rebound effects, which play an important role in the effectiveness of energy efficiency policies.

The price-responsiveness of transport energy demand has been explored of different IAMs. Five IAMs, namely IMAGE, MESSAGE, POLES, REMIND, TIAM-UCL and WITCH have participated to the exercise. So far, we have focused on price elasticities, analyzing the fuels own and cross elasticities, but aim to extend the analysis to elasticity of substitution between fuels and potentially between energy and efficiency investment. Moreover we plan to test the models income elasticities. In this chapter the scenario set-up used to analyze the price and income elasticities are first discussed, after which some preliminary results of the model price demand response are shown, and finally the next steps are laid out. This work is a joint WP2/WP3 effort and while in this report the initial results for the transport sector are described, it will be further elaborated, and for other demand sectors in deliverable 3.4.

1.5.2. Scenario set-up

16 scenarios have been designed to calculate the price-demand elasticities for the transport sector. Similar work has been done previously to test elasticities inherent in energy system models, and we have designed our scenarios inline with these studies (Hogan & Sweeney, 1981; Mark Jaccard, 2014). In the scenarios the fuel prices are shocked from 2020 onwards with a price change with respect to baseline of -50%, 50% and 100%, used to look at price-demand effects at different periods in time (e.g. 2025, 2050, 2070). Based on experience with demand response to carbon price, or taxes and subsidies, the expectation was that shocks of 50-100% compared to reference fuel prices (at any point in time) were needed to get significant demand response. The shocks are applied to Oil & Gas, Coal, Biofuel and Electricity. The fuel price is increased at the final energy level for all demand sectors. The focus of the initial analysis is on the transport sector demand response, but the same scenarios can also be used for analysis of implicit elasticities in other demand sectors.

The price increase is added as exogenous shock. This can be implemented by reading in final energy prices exogenously, but alternatively the change in final energy prices can be implemented as a tax or subsidy. In that case feedback effects in the model will potentially result in final energy prices moving away from the shock applied and converging to the original price path in the longer time frame, as a result of e.g. changes in depletion behavior. However, since 1) for many models it will be impossible to implement this in another manner, 2) price demand elasticities can still be calculated even if the % price change is not exactly the same 3) it might interesting to compare how large the indirect effects are between models, the scenario are designed in this manner. The percentage increase with respect to baseline fuel prices is applied during the whole time period, for each region. For example if the

[3] The price and income elasticity work is planned to be submitted to the special issue "Transport in IAMs" in the journal Transportation Research Part D: Transport and Environment.

fuel price of a certain fuel in a certain region was originally in the baseline 1$/MJ in 2020 and 3$/MJ in 2040 than it would be 1.5$ in 2020 and 4.5$ in 2040 in the +50% increase scenario.

The price-demand scenario set looks as followed:

Scenario		**Price jump w.r.t. baseline per FuelType**			
	Name	Oil & Gas	Electricity	Biofuel	Coal
1	ADV2-TRA-BASE-FullTech	Ref	Ref	Ref	Ref
2	ADV2-TRA-PE-OG1	-50%	Ref	Ref	Ref
3	ADV2-TRA-PE-ELE1	Ref	-50%	Ref	Ref
4	ADV2-TRA-PE-BIO1	Ref	Ref	-50%	Ref
5	ADV2-TRA-PE-COA1	Ref	Ref	Ref	-50%
6	ADV2-TRA-PE-ALL1	-50%	-50%	-50%	-50%
7	ADV2-TRA-PE-OG2	+50%	Ref	Ref	Ref
8	ADV2-TRA-PE-ELE2	Ref	+50%	Ref	Ref
9	ADV2-TRA-PE-BIO2	Ref	Ref	+50%	Ref
10	ADV2-TRA-PE-COA2	Ref	Ref	Ref	+50%
11	ADV2-TRA-PE-ALL2	+50%	+50%	+50%	+50%
12	ADV2-TRA-PE-OG3	+100%	Ref	Ref	Ref
13	ADV2-TRA-PE-ELE3	Ref	+100%	Ref	Ref
14	ADV2-TRA-PE-BIO3	Ref	Ref	+100%	Ref
15	ADV2-TRA-PE-COA3	Ref	Ref	Ref	+100%
16	ADV2-TRA-PE-ALL3	+100%	+100%	+100%	+100%

Table 1. Price Elasticities Scenarios

1. Income elasticities

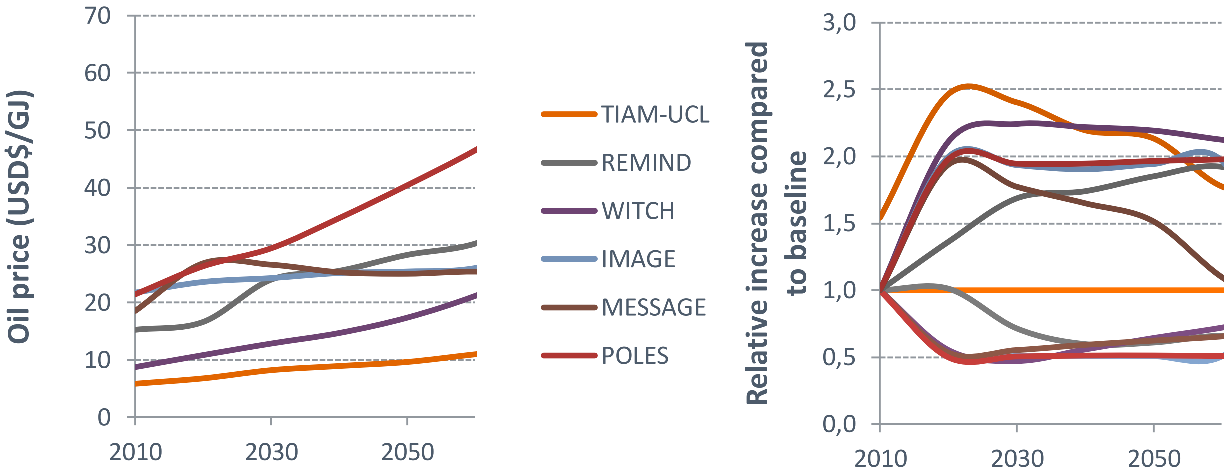
To look at income-demand effect, in addition to the price-demand scenarios 2 extra scenarios are added to the scenario set. In these scenarios the GDP path assumption are adjusted to investigate the income-demand elasticities. In the baseline scenario the models have been asked to implement the Share Socio Economic Pathway (SSP) 2 assumption for GDP and population growth. These additional scenarios follow the SSP1 and SSP3 income paths in an SSP2 world. Those models that can easily keep the fuel price paths identical to the reference scenarios are encouraged to do so, to decouple income effects from price effects, but this is not a requirement. The SSP1, SSP2 and SSP3 GDP path assumptions can be downloaded from https://secure.iiasa.ac.at/web-apps/ene/SspDb. Model teams have currently uploaded the income elasticity scenarios, but the analysis of the scenarios results will be part of Deliverable 3.4.

Scenario		**Income jump**
	Name	
17	ADV2-TRA-IE-HIGH	GDP path follows SSP1 GDP assumptions
18	ADV2-TRA-IE-LOW	GDP path follows SSP3 GDP assumptions

1.5.3. Preliminary results

The price scenario have been run by IMAGE, MESSAGE, POLES, REMIND, TIAM-UCL and WITCH. Figure 10 on the left shows the models original oil price in the baseline scenario, while to the right shows the relative oil price reduction in the -50% scenario and + 100% scenario, running from 2010 to 2060. The results show that global oil prices have a broad range in 2010 across the models. Most models project fossil fuel prices to increase, likely due to depletion effects. The uncertainty in oil prices across the models will ultimately result in varying fuel shocks in absolute terms, as in the scenario design the shocks are applied with respect to the baseline scenario fuel prices. The time elapsed until the full shock of + 1 or – 0.5 is achieved is slightly longer in REMIND compared to the other participating models (Fig b). Both in MESSAGE and TIAM UCL oil prices are moving away from the shock toward the end of the century.

Figure 10 Baseline oil price (left) and the relative increase in oil price compared to baseline (right).



In Figure 11 the electricity and oil response to the price shock scenario are shown in 2030 and 2060. In 2030, ten years after the applied shock, all models show limited electricity demand response, increasing slightly in the high oil price scenarios. The oil demand responds to the fuel price changes in 2030 in all models and this effect is much larger in 2060 (Fig b). MESSAGE oil demand ranges from 35 to 290 EJ per year, while due to the feedback effect the fuel price range by then is relatively small. In other models (e.g. POLES) the fuel price range is very broad, amplified by the large increase in oil price toward the end of the century in the baseline. WITCH and POLES shows a mild response to the changing fuel price, while IMAGE, REMIND and TIAM UCL all show significant response.

Finally the oil price elasticity values of the models for each scenario are calculated for 2030 and 2060 (Figure 12) :

Equation 2

$$E_{x,y} = \frac{\%\ change\ in\ price\ x}{\%\ change\ in\ demand\ y}$$

where the percentage change in going from point 1 to point 2 is calculated relative to the midpoint. Most models respond more heavily to an increase in oil price than a decrease. In the literature long-term gasoline elasticities range from -0.6 to 0.9 (Burke & Nishitateno, 2013), which is in the same order of magnitude with the results that can be found in IAMs in 2030. In 2060 the demand response is more sensitive to price differences. MESSAGE shows small price differences in 2060 small while demand differences large resulting in very high elasticities or even negative elasticities. This shows that the energy system has completely changed after 40 year high oil fuel prices, and the demand change is the effect of the oil price in the previous years. In POLES the opposite effect is visible with oil demand responds less as time proceeds.

Figure 11 The oil (triangle) and electricity (square) demand response to oil price shocks.

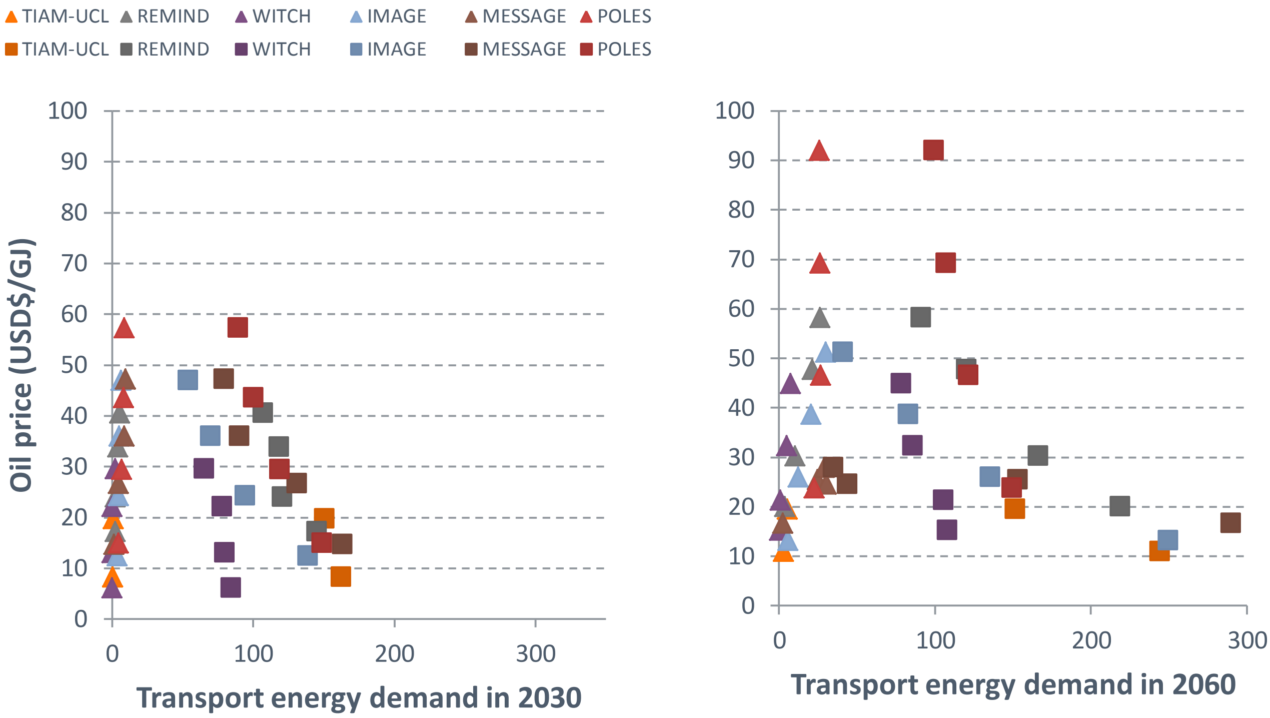
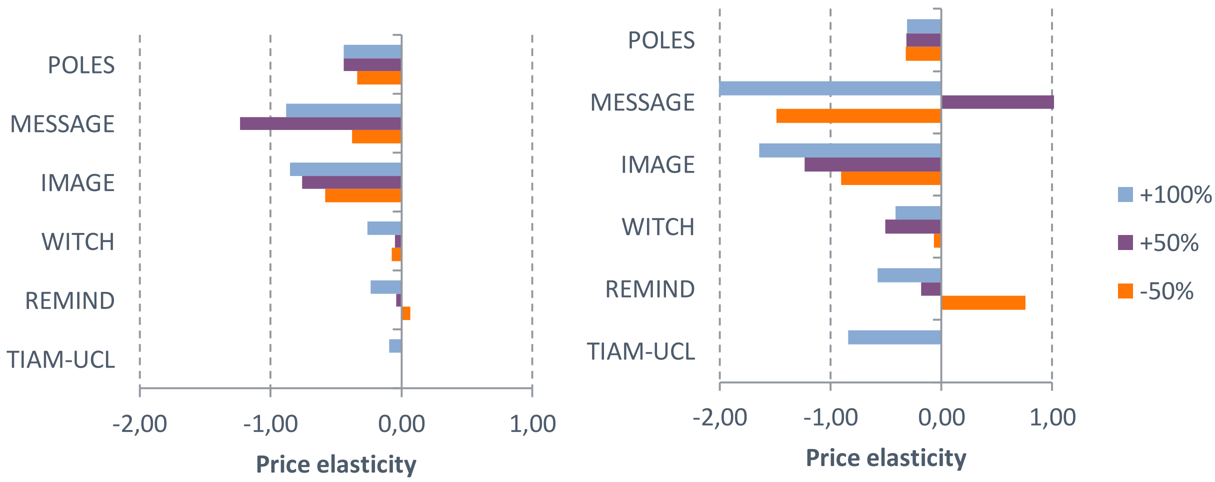


Figure 12 Oil demand elasticity in 2030 (left) and 2060 (right).



1.5.4. Conclusion and discussion

Price and income elasticities of fuel demand in the demand sectors represented in IAMs can be compared to better understand model behavior. A scenario protocol has been set up within the ADVANCE project to calculate these price elasticities. So far the analysis has focused on transport sector oil prices, where it was found that ten years after the shock implementation, although there is a significant range between the models, the elasticities are comparable to empirically found historical gasoline price elasticities (Burke & Nishitateno, 2013). In 2060 (thirty years later) model results are less straightforward to compare as the effect of the shock has in some models faded away due to feedback effects, while in others the fuel price have increased over time resulting in a range of 28 and 90$/GJ for oil prices in the + 100% scenario. The results however do give insight in whether the models are responsive or less responsive to changing fuel prices, the delay in response time, in the longer and in the short term.

This research is planned to be extended to other fuel types, looking in to cross elasticities and elasticity of substitution. The same set of scenario can be applied to other demand sectors as well. Eventually, the aim is to compare the model elasticities to elasticities in economic models.

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2. Buildings

2.1. Introduction

In 2010 32 % percent of the final energy use was consumed in buildings, and 19% of global GHG emissions (including indirect emissions from electricity production) were emitted. The fifth assessment report of the IPCC concluded that the energy demand in buildings could double or even triple if current trends continue. Key developments that result in increasing demand are population growth, increased wealth, household size change, changing lifestyle, migration to cities, and increased access for billions of people to adequate housing (IPCC WGIII CH.9 Lucon et al., 2014).

The buildings sector consists of residential and service sector buildings, which can be divided over many different sub-sectors (hotels, warehouses, hospitals, schools etc). There is a wide range of measures that can be applied in buildings affecting energy use, for example in the building envelope but also efficient use of appliances and lighting (IEA, 2014). Cost effective and best practice technologies have a high potential to reduce emissions (Lucon et al., 2014). According to the IEA, unlike the transport sector and industry sector where technologies are dependent research and breakthroughs in the building sector most technologies have commercial viability. A combination of R&D and economies of scale could still improve the technologies performance and affordability (IEA, 2014).

More specifically individual new buildings can reduce their energy requirement with two to ten fold, and existing buildings with two to four fold, through a combination of recent technology development and behavioral change. High performance building envelope can reduce heating demand with 70-80 % in cold OECD countries and 60-90 % of cooling demand in hot countries. Heating demand account for the largest end use share in buildings but appliances and electronic equipment are the fastest growing energy end use and are projected to continue to grow fast. Lighting and appliances have a significant potential for energy use decrease through deployment of more efficient technologies. Improved design of buildings and better use of natural light can decrease light demand even further (IEA, 2014).

In the residential sector cooking is one of the largest end uses accounting for almost 20% of global buildings energy use. In certain countries in Africa and in Asia it accounts for 50% of residential energy use. Low cost efficient cook stoves are a critical measure to reduce the energy use and use of traditional biomass for cooking, with as co-benefit to reduce the polluting emissions.

Due to the long life span of buildings the risk of lock in effects in large and the impact of immediate action is high. Experience shows that regulation and policy programs to induce efficiency standards are more effective than pricing mechanisms to improve energy efficiency in buildings. The rapid increase in energy use in the buildings, along with the technology development and inertia of the sector makes it highly policy relevant to assess different pathways of buildings energy use.

In this chapter first an overview of how the residential energy use has been modelled in eleven IAMs participating in ADVANCE is presented, while identifying the main model improvement directions. In Section 2 building model development that has taken place during the time span of ADVANCE project are described in detail. In Section 3 the model scenario projections of IMAGE, AIM/CGE, iPEts, MESSAGE and POLES follow. Finally the chapter ends with a discussion section where current limitations and possible opportunities are discussed.

2.2. Stocktaking – description of current residential models

Overview of the IAM Residential energy use

Eleven IAMs have completed the questionaire that was send out to the FP7-ADVANCE consortium, i.e. TIAM-UCL, WITCH, DNE 21+, IMAGE, iPETs, Imaclim-R, AIM-CGE, GCAM, POLES, GEM-E3 and REMIND. The questionaire contained open questions on how *residential* energy use was modelled. Table 1 and 2 present the summarized results of this questionaire. Apart from REMIND and WITCH, all models include an explicit description of residential sector energy demand. Table 1 focuses on the energy demand determinants and the system boundaries. The residential sector system boundaries are defined vary throughout the models. GEM-E3 and AIM-CGE, for example, take passenger transport in to account within the residential sector. What is included under indirect energy use (beyond final energy) is not entirely clarified by the responses gathered through the questionaire.

GCAM, IMAGE, DNE 21+ and TIAM-UCL model a high variety of energy functions explicitly, such as refridgerators, heating, cooling, water heating, lighting and appliances. Identifying the drivers of the demand for these energy functions and modelling them explicitly to project energy use in buildings has a couple of advantages:

- The demand for certain energy end uses (space heating, water heating, space cooling) are strongly correlated to climate conditions. Modelling this relation in a global energy model can improve the understanding of regional differences.
- Technology efficiency can be related to specific end uses which can improve the projection of energy efficiency potential. For space heating for example boilers technology efficiency improvement space is limited, but there are many measures that can be taken to improve insulation of the building. These measures come with specific costs and considerations, such as the lifetime of the technology. Modelling technology efficiency also gives the opportunity to model technology specific policy.
- Different end uses are suitable to be fueled by different types of energy carriers. Cooking for example historically has been fueled for a large share by traditional biomass in less developed regions. By modelling end uses explicitly historical trends can be explained, and the potential of fuel switching can be quantified. Similar considerations can be made for the cooling, appliances and lighting shares, which generally can only be fueled by electricity.

In sum modelling the demand of energy end uses can improve the understanding of the possibilities to improve energy efficiency and CO_2 efficiency, and the role of structural change in time, as well as regional differences.

The models relate the energy function demand to economic and demographic drivers combined with function specific drivers, such as floor space indicating space requirements (space heating and space cooling), and cooling degree days and heating degree days relating to climate conditions.

The general equilibrium models use a different approach. Imaclim-R uses a building stock model which relates buildings floorspace to household revenue per capita, which is a model outcome. Energy consumption per square meter follow exogenous trends for “conventional buildings”. “Low energy building” penetrate the building stock when policies are implemented. Also GEM-E3 and iPETs represent energy use in buildings at a household level. The representative household firstly decides on the allocation of its income the different consumption categories available. In GEM-E3 the consumption categories are split in non-durable consumption categories (food, culture etc.) and services from durable goods (cars, heating systems and electric appliances). The household income is a calculated endogenously in the model and spent in such a way that utility is maximised. The advantage of modelling household specifically is that clear differences in energy use (e.g multi family vs. single family) and differences in efficiency improvements (e.g. new buildings vs. existing buildings) can be modelled explicitly.

In AIM-CGE residential energy demand is based on GDP and population in combination with its elasticity. The optimization models REMIND and WITCH use a CES (constant elasticity of substitution) production based on GDP and autonoums efficiency improvements to substitute between capital and energy. More details can be found in Table 1.

Table 2 shows further detail on technology assumptions and allocation of market shares across different technologies and fuels. TIAM-UCL, IMAGE and DNE21+ model multiple discrete technologies to fufill the functions energy demand. The other models specify different fuel and efficiency improvements (either exogenous or endogenous), but do not explicitly model technologies. IMAGE, POLES and GCAM use a logit function to distribute the technology shares. In REMIND and WITCH the technology shares follow cost optmization, where the cost is based on lifetime, investment cost, O&M costs and learning rates. TIAM UCL choses technology investment in such a way that the consumer and producer surplus is maximised.

Finally in Table 3 the model improvement as planned within the ADVANCE project are discussed. Two main improvements can be identified:

1) Representation of energy end uses, allowing explicit analysis of separated residential demands, which can offer context to the changes of energy carrier shares and efficiency over time, and between regions.

2) Representation of the energy use within a building and better description of the building stock, which allows analyses of the capital requirements and building stock turnover implied by energy efficiency improvements. With that allows for assessing the lock-in of inefficient technologies in delayed scenarios and giving the opportunity to assess efficiency standards.

	TIAM-UCL	IMAGE	iPETs	Imaclim-R version 1.0	AIM-CGE	POLES
Model type	Bottom-up, partial equilibrium	Hybrid, Long term simulation	Top down	Hybrid, General equilibrium simulation	Top-down, General equilibrium	Hybrid, Simulation
System boundries/functions	**11 functions:** Cooling, Clothes Drying, Clothes Washing, Dishwashing, Other Electric, Space Heat, Hot Water, Cooking, Lighting, Refrigeration, and Others.	Energy consumption within the house. **6 functions:** Lighting, cooking, space heating, space cooling, water heating, appliances.		This question does not apply to a general equilibrium model. No explicit functions.	No indirect energy use is included. Passenger car is included.	Energy use represents precisely the final energy use. CHP is accounted for in the power production system. **2 functions:** Captive electricity and Substitutable needs
Drivers/determinants and relationship with the energy demand	Energy service demands are projected using general economic and demographic drivers (pop, GDP). To develop projections, estimates of drivers are used in conjunction with user assumptions on the coupling factor of demands with drivers.	Direct (exogenous) drivers: GDP, Population. Indirect (exogenous) drivers: Urbanization, inequality (GINI coefficient), population density, electrification. Endogenous drivers: Floor space, Heating/Cooling degree days	Household consumption of final goods is derived from income and (optimized) savings. Preferences for consumption goods are derived from underlying demograpic structure changes and change with income level.	Higher building stock result in higher energy demand. Low energy buildings penetrate the building stock when policies are implemented. Penetration of low energy buildings reduces energy demand. Drivers: Population (ex), household revenues/capita (end), energy consumption/m2 meter of conventional buildings (ex).	Per capita energy demand is determined by GDP/cap with its elasticity and population is multiplied. We separate energy demand from general utility function.	Drivers: GDP per capita, derived into floor surface for heating / cooking / hot water demand. Energy prices, energy costs, degree-days. Energy demand increases with surface / GDP per capita, and is negatively affected by energy costs that can spur insulation.

	GCAM	REMIND	GEM-E3	WITCH	DNE 21+
Model type	Hybrid, Simulation	Hybrid, Inter-temporal optimization	Top down, general equilibrium	Top down, optimization	Hybrid, Linear program optimization
System boundries/functions	Includes all energy demanded by the residential sector, and all energy used to produce this energy, but not building materials or emissions from equipment manufacturing. **7 functions:** heating, cooling, water heating, lighting, appliances, and other.	The indirect energy use and material needs for production of appliances is not explicitly included, only implicitly embedded in the main CES production function. All the energy use for extraction and conversion of energy is represented up to the distribution of final energies. **2 functions:** electricity used for appliances, and all other inputs for heating purposes.	Household consumes energy through: i) Heating & Cooking and ii) Operation of transport. Both consumption purposes are associated with the consumption of specific energy forms through fixed factor coefficients implied by the consumption matrix. The residential part of model includes explicitly energy demand for heating and cooking and for operation of transport.	Final energy is required in different forms (electricity, and non-electric energy)	The residential sector corresponds to building sector in the DNE21+ model. **5 functions:** Refrigerators, lighting, TV sets, air conditioners and gas stove
Drivers/determinants and relationship with the energy demand	Population: linear impact on floor space. Floor space: linear relationship on service demands. GDP: satiation demand functions used between GDP and floor space, and between GDP and all individual buildings services. Heating and cooling degree days: Changes from base-year influence the heating and cooling demands per unit of floor space.	GDP growth, the autonomous efficiency improvements, the elasticities of substitution between capital and energy and between stationary and transport energy forms. Final energy types are input to a CES function, the output of which is combined with transport energy in a CES function to generate a generalized energy good, which is combined with labor and capital in the main production function for GDP.	The representative household receives income from labour supply, ownership of other production factors and transfers from the rest of the world. Household exhausts its income in order to maximize its utility. Consumption over the different commodities is based on their relative prices. Energy demand is influenced by energy prices, the stock of durable goods for each households income. Energy required for the use of appliances and vehicles is determined once the utility maximizing choice is made over	GDP, Population, autonomous energy efficiency improvement Overall output consists of a CES nest of a capital-labour aggregate and energy services (ES). ES combines Energy RnD and Energy (electric and non-electric	Penetration of appliances and their utilization ratio depend on population, GDP and cooling degree days, while technological improvement and implicit discount rate affects consumer’s technology choices.

the level of durable goods.	energy).

Table 1: Drivers of energy demand in the residential sector of ten IAMs.

Table 2: Technologies and final energy carriers

	TIAM-UCL	IMAGE	iPETs	Imaclim-R version 1.0	AIM-CGE	POLES
Technologies	Heating and other services have up to 7 competing fuels, and cooling has up to 2	Cooking (6), appliances (8), space heating (6), space cooling (3), water heating (6), lighting (3)	N/A	N/A	water heating (5), cooking (5), lighting (5), space heating (5), space cooling (44), other electric equipment (1),	Different types of heaters.
Final energy carriers	Natural Gas mix, Heavy fuel oil, diesel, Kerosene, Coal, LPG, Bio-fuels, Geothermal, Solar, Electricity (hundreds of generating options), Heat	Coal, modern biofuel, traditional biofuel, liquid fuels, gaseous fuels, electricity (can ben generated from coal).	Coal/biomass, Electricity, other energy (= refined fuels and natural gas)	Coal, gas, liquid fuels, electricity. Liquid fuels from fossils or from biomass. Electricity from coal, gas, oil, w/wo CCS, nuclear, hydro, other renewables	Coal, gas, liquid fuels, electricity. Liquid fuels from fossils or from biomass.	Energy carriers: oil, gas, coal, biomass modern, biomass traditional, H2, electricity, steam. Electricity and low temperature steam can be produced locally.
Determinants technology application	Technology investment and activity is chosen based on the mix that maximizes the entire model consumer + producer surplus, subject to technical, climate, physical constraints, assumed costs, policies.	A multinomial logit function is used, which distributes the technology shares based on their costs.	N/A	N/A	A multinomial logit function is used, which distributes the technology shares based on their costs.	Competition (logit) is based on cost for the user (fuel price, heater cost, efficiency), and is calibrated on historical market shares. Energy efficient buildings penetrate as a function of the ROI of the energy savings.
Technology costs	The technology parameters change over time in the sense that new technologies become available which have improved efficiency and different costs, which may decrease over time.	Annualized investment costs, annual fuel costs. Efficiency of appliances and end use function increases exogenously based on literature. Consumer discount rates decrease as income increases	N/A	N/A	Annualized investment costs, annual fuel costs. Energy device information such as cost, efficiency is based on AIM/Enduse (Akashi et al., 2012)	Costs and efficiencies are exogenous, and do not change over time.
	GCAM	**REMIND**	**GEM-E3**		**WITCH**	**DNE 21+**

Technologies	USA: 25, China and India: but no further disaggregation is done past energy service and fuel type. Other regions: heating and other services have competing fuels; cooling does not.	None	Energy efficiency can be improved endogenously (factor substitution) or exogenously (imposition of energy efficiency standards). There are no discrete technologies but an energy efficiency cost curve is used.	N/A	Size, Type, Prices and Performance w.r.t energy efficiency
Final energy carriers	Biomass ,Coal, Gas, Liquid fuels (from oil, gas, coal, and biomass). Electricity (from coal, gas, oil, biomass, nuclear, hydro, geothermal, solar, and wind)	Electricity (from Coal, Gas, Oil, Biomass, Wind, PV, CSP, geothermal, hydro or nuclear), Heat use (from Coal, Gas, Oil or Biomass, and can be combined. with CCS) Gases can come from Natural Gas, Coal or Biomass, District Heat CHP, Coal, Biomass, Gas, heat pumps using electricity)	Residential sector consumes oil, gas, biomass and electricity (coal fired, oil fired, gas fired, nuclear, hydro, biomass, wind, pv, ccs coal, ccs gas).	Only implicitly modeled: Electricity Traditional Biomass (in developing countries) Oil (Heating) Coal (Heating) Gas (Heating/Cooking)	Solid fuels [coal, biomass], Liquid fuels [gasoline, light oil, heavy oil], Gaseous fuels [natural gas, hydrogen] and Electricity
Determinants technology application	There is a logit share function that allocates the shares to competing options according to average levelized cost of service provision. The function is calibrated to actual base year shares, and absent any fuel or non-fuel price changes, will replicate the observed base-year shares in all future periods.	Technology choice follows cost optimization based on investment cost, O&M cost, fuel costs, Emission costs, efficiencies.	The energy mix is decided according to changes in the relative price of fuels. Once a consumption function is decided the share and mix of energy consumption is defined by fixed factor coefficients through the consumption matrix	Substitutability and cost optimization based on capital, O&M, Emissions, and fuel costs and relative efficiencies.	The total energy system cost to fulfill the energy demand is minimized with combination of costs of bottom-up individual technologies and costs (loss of consumption utility) for top-down areas.
Technology costs	The costs generally decline modestly over time—at either 0.1% per year or 0.25% per year. The fuel costs are derived from the efficiency (exogenous) and the energy cost (endogenous). The non-fuel costs of each technology are from assumed capital costs, discount rates, equipment lifetimes, and fixed and variable O&M costs.	All of these: efficiency, lifetime, investment costs, fixed and variable O&M costs, learning rates.	The estimation of energy efficiency cost curves includes: i) initial energy intensity, ii) average cost for energy efficiency, iii) potential for energy efficiency (upper bound of the curve). Technology costs change over time through exogenous assumptions and through the accumulated stock of energy efficiency investments.	Efficiency, Investment Costs, Lifetime, fixed and variable O&M costs, learning rates (in renewable technologies), RnD investment for electric backstop and nonelectric backstop	Investment cost, implicit discount rate, operation and maintenance costs, efficiency, and lifetime are given exogenously.

	TIAM-UCL	IMAGE	iPETs	Imaclim-R version 1.0	AIM-CGE	POLES
Model development	We will not focus on the residential sector, but since we plan to disaggregate demand for passenger transport based on population cohorts, we may end up disaggregating also the residential demands	Within the ADVANCE project we are planning to build a service sector model where the demand for the energy end uses is explicitly modelled, similar to our residential model	We currently aggregate all household types into a single representative household. A major improvement is to develop downscaling/microsimulation tools to disaggregate the	N/A	Conventional CGE model uses just simple consumption function (e.g. LES) for the residential sector and production function (CES) for the commercial sector. Within	1. further split of energy services with explicit representation of heating, cooking, hot water, cooling; introduce role of climate; 2. detailed representation of the complete energy balance within a building

			household sector outcomes to multiple household types.	ADVANCE, we have developed the model which explicitly treats detailed energy enduse technolgies.	The third improvement (better description of the building stock) will depend on time and resource availability.
	GCAM	**REMIND**	**GEM-E3**	**WITCH**	**DNE 21+**
Model development	N/A	1. Separation of industrial and residential energy demand; 2. stylized representation of the end-use technology stock determining the efficiency of energy use in buildings, so that energy service activity levels such as heated and cooled floor space can be analyzed	Extention of each energy function so as to include a number of processes/technologies. The main idea is to expand the micro-economically founded modeling of agent behavior by modeling explicit technologies in discrete choices and by introducing cost-potential functions for the resources.	Build a separate residential demand model, include behavioral aspects of energy consumption and investment in energy efficiency improvements	N/A

2.3. Residential sector: Example of modelling demand drivers and efficiency in IMAGE[1]

Residential energy use plays an important role in achieving a more sustainable development. First of all, residential energy use represents about 35% of global energy use and it therefore plays a key role in global energy-related environmental problems such as climate change and resource scarcity (IEA, 2004, 2007). Urban air pollution and indoor air pollution are even more tightly related to residential energy use. Secondly, sufficient access to modern energy also forms a necessary condition for economic development and human well-being. In 2000, the international community made a commitment to the Millennium Development Goals (MDGs); a series of quantitative and time-bound targets aimed at tackling, among others, poverty, hunger, health, equality and environmental sustainability. Modi et al. (2005) and the IEA (2010) both show that access to modern energy forms a necessary condition for achieving these goals.

Model-based scenario analysis forms an important tool to explore the relationships between residential energy use, development and environmental issues. Most global energy models describe future residential energy demand based on relatively simple relationships between energy consumption and income or GDP per capita. This implies that trends are only understood in abstract variables such as energy intensity. Moreover, specific dynamics of developing countries, such as underdeveloped markets and informal activities, the transition from traditional to commercial fuels, electrification, the role of income distribution and the urban/rural difference are not modeled at all (Pandey, 2002; Shukla, 1995; van Ruijven et al., 2008a). Subsequently current energy models tend to give poor results for developing countries (van Ruijven, de Vries, van Vurren, & van der Sluijs, 2009).

A number of key energy functions (and associated drivers) play a role in residential energy use. Such functions include space heating and cooling, lighting, water heating, appliances and others (Howell, Alfstad, Victor, Goldstein, & Remme, 2005; Pachauri, 2004; Schipper, Haas, & Scheinbaum, 1996). Modeling these energy functions allows the study of the dynamics and possible future trends in this sector. Very few models currently follow such 'bottom-up' approach at the global scale, although some models exist for specific functions (Ekholm, Krey, Shonali, & Riahi, 2010; Isaac & van Vuuren, 2009; McNeil & Letschert, 2007; McNeil, Letschert, & de la Rue du Can, 2008).

This study attempts to understand and subsequently project world-wide residential energy use using a bottom-up energy model which takes the heterogeneity of the residential sector in developing countries into account. The model (Residential Energy Model Global, REMG) described in this paper is based on an explicit representation of five energy functions in households and their main drivers for 26 world regions. Within each region, the model addresses heterogeneity by distinguishing between urban and rural population classes and furthermore disaggregates between income quintiles of the respective classes. In this paper the model is used to focus on detailed projections for residential energy use in India, China[2], South East Asia[3], South Africa and Brazil. These countries/regions were selected due to their importance for global energy use as "newly industrialized economies", but also based on their climatic and social-economic differences. More specifically this paper deals with the following questions:

1. Given the data availability, is it possible to adequately model residential energy use on a global scale in a bottom up fashion?

[1] *The description of model improvement is a summary of the following article:* Vassilis Daioglou, Bas J. van Ruijven, Detlef P. van Vuuren (2012), *Model projections for household energy use in developing countries*, Energy, Volume 37, Issue 1, January 2012, Pages 601-615, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2011.10.044.

[2] The China region consists of China, Hong Kong, Macau, Mongolia and Taiwan.

[3] South East Asia is made up of: Brunei Darussalam, Cambodia, East Timor, Indonesia, Laos, Malaysia, Myanmar, Papua New Guinea, Philippines, Singapore, Thailand and Vietnam.

2. What are the future trends of the residential energy use for India, China, South East Asia, South Africa and Brazil, and how do these trends differ?
3. What is the impact of specific policy interventions aimed at reducing greenhouse gas emissions in these five regions?

The REMG model is an expanded version of a model developed specifically for the Indian residential sector (van Ruijven et al., 2011). This model has been adapted for analysis of other regions and validated based on available historic data. It has been used to describe possible future trends based on the scenarios currently being developed by the Global Energy Assessment (IIASA, 2010). These scenarios are attractive in the context of this paper given their focus on environmental and development issues. Using the GEA scenarios, we look into possible developments under different assumptions for socio-economic development – but also on the impacts of climate policy by introducing a carbon tax.

In this paper, section 1 explains the methodology used by outlining the REMG model and a qualitative description of the scenarios is given. Section 2 summarizes the results of the baseline projections and the sensitivity analysis. Section 3 describes emissions pathways and the results of the climate policy scenario. Finally, section 4 offers a discussion on the methodology as well as some conclusions from the results.

Residential Energy Model – Global

REMG is a stylized bottom up household energy simulation model which describes the demand and supply of energy for different household energy functions (Daioglou, 2010; van Ruijven et al., 2011) (Daioglou, 2010). There are a few key concepts that can be derived from the available literature on residential energy use. First of all, energy use in the residential sector can be best understood by focusing on specific end use functions and their drivers (Howell et al., 2005; Schipper et al., 1996). By relating these functions to economic development it is thus possible to analyze changes in energy use. Secondly, in the literature, the concept of the energy ladder is often used to describe empirical trends of fuel switching from traditional fuels (e.g. wood and coal) towards modern fuels (natural gas and electricity) (Hosier & Dowd, 1987). Finally, an important factor in residential energy use is the recognition of heterogeneity. Based on earlier research, income groups and urban/rural classes have been identified as the most statistically significant in determining a households' energy consumption patterns (Pachauri, 2004).

Figure 1 shows how in the model the primary drivers, secondary drivers and energy functions are related. In total, the model focuses on the five most important end use functions (IEA, 2004): i.e. cooking, appliances, space heating and cooling, water heating and lighting (these relationships are discussed in greater detail in A.1 End Use Functions REMG model). The energy demand for the end-use functions is determined on the household level. The model uses five income quintiles for both the urban and rural population (population classes). After determining the energy demand per function (for each population class), supply by fuel type is determined on the basis of relative costs. Throughout this paper 'traditional biomass' and 'coal' are referred to as 'solid fuels' while the rest are considered 'modern fuels'. The REMG model in principle also describes more advanced fuels such as hydrogen and modern bio-energy but given our focus on scenarios up to 2030, we have decided not to include these fuels here. In this paper REMG is applied as a stand-alone model. However, it is normally applied within the energy system model TIMER (van Vuuren et al., 2007) allowing to capture feedbacks between energy demand and energy prices.

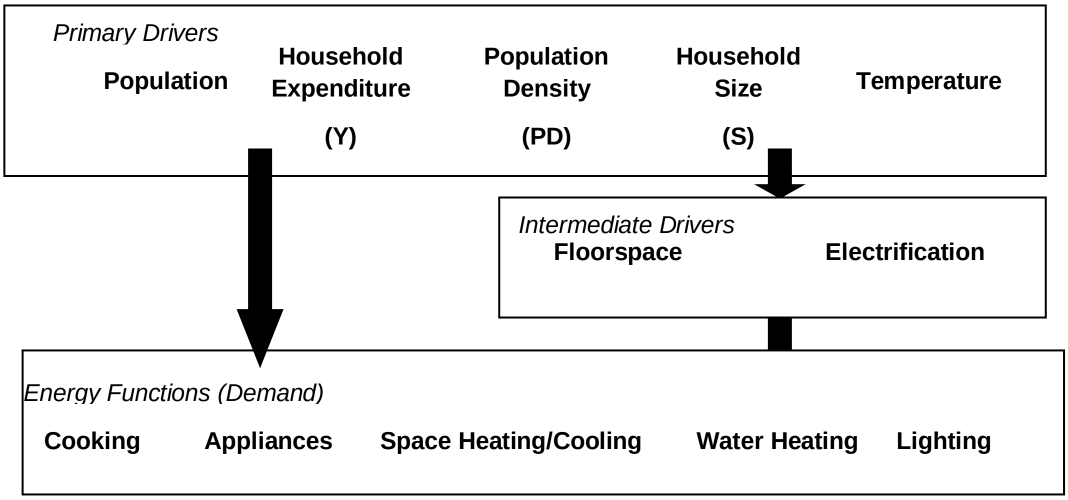


Figure 1. Relationship between drivers and energy functions; all drivers (except for population density and temperature) defined for urban/rural classes and income quintiles. The relationships between these parameters are described in section A.1 End Use Functions REMG model.

It should be noted that the data requirement of the REMG model is considerable. Data is required for the drivers such as household expenditures, household sizes and income inequality. Data is also required for the energy consumption for the end use functions in relation to these drivers. This includes ownership rates and unit energy consumption of household appliances and data on useful energy requirement for cooking and heating. Finally, information concerning fuel choice for each end use function is needed. Unfortunately, such data are often not available from international data sources. We therefore had to consult many national data sources. While important data gaps remain, especially in time series, we were able to find enough data to determine relationships and calibrate the model

Household information and appliance ownership was primarily collected from censuses and surveys of each country but also from the *World Development Indicators* of the *World Bank* (NBSC; NIS, 2009; NSSO, 1997, 2004; SSA, 2002, 2007; WDI, 2009). For income inequality, databases of the World Bank were used (World-Bank, 2009, 2010). Total final consumption of energy for the residential sector on a global scale is available from the International Energy Agency, which also breaks down the energy use to different fuels (IEA, 2007). More detailed data concerning the urban/rural divide, energy use per energy function, fuel shares, fuel subsidies etc, were gathered from scientific papers and independent databases (Gangopadhay, Ramaswami, & Wadhwa, 2005; Jannuzzi & Sanga, 2004; LBNL, 2008; Peng, Hisham, & Pan, 2010; Tonooka, Liu, Kondou, Ning, & Fukasawa, 2006; Xiaohua, Xiaqing, & Yuedong, 2002). Data concerning the difference in cooking fuels between urban and rural households is available from the *World Health Organization* (WHO, 2010). The model was calibrated against the available data in order to ensure that key indicators match historic observations. The calibration consists of data regression and manual parameter estimation and is aimed to ensure that household properties, appliance ownership, cooking fuel choice and final energy use reflected the data mentioned above as much as possible.

Baseline Projections

The following paragraphs describe the model results (final energy use) for different regions as well as a sensitivity analysis. We first discuss total residential energy use, and next focus on the different end-use functions as well as the use of electricity. Where appropriate, the difference between urban/rural localities and income quintiles are also highlighted. Since this paper focuses on development the results presented focus around energy functions, fuel use and access to clean cooking fuels.

Total Residential Energy Use

In all regions, the assumed income increase in the baseline scenarios leads to an increase in energy demand for different energy functions and a diversification of the fuel supply. Figure 2 shows the projected final energy use by end use function in 2007 and in 2030 under the baselines for each of the studied regions for urban and rural households.

As shown in Figure 2 (by comparing 2007 and 2030 columns), the first end-use functions that are met are cooking and lighting. While lighting energy demand only forms a small share of total demand, in most regions cooking forms the most dominant end-use function. As households get richer, energy use for appliances, space heating/cooling and water heating gain importance. In China and South Africa space and water heating are projected to become important for energy given the climatic conditions. In contrast, in India, South East Asia and Brazil space cooling is more important.

For urban energy use, appliances and cooling become important end-use functions, while for rural energy use cooking continues to dominate the picture for a much longer period of time. The exception here is formed in China and South Africa where space heating also is important for rural households (again, as a result of climatic conditions). Appliance energy use and space cooling are lower in rural regions due to lower income levels, but also lower electrification rates.

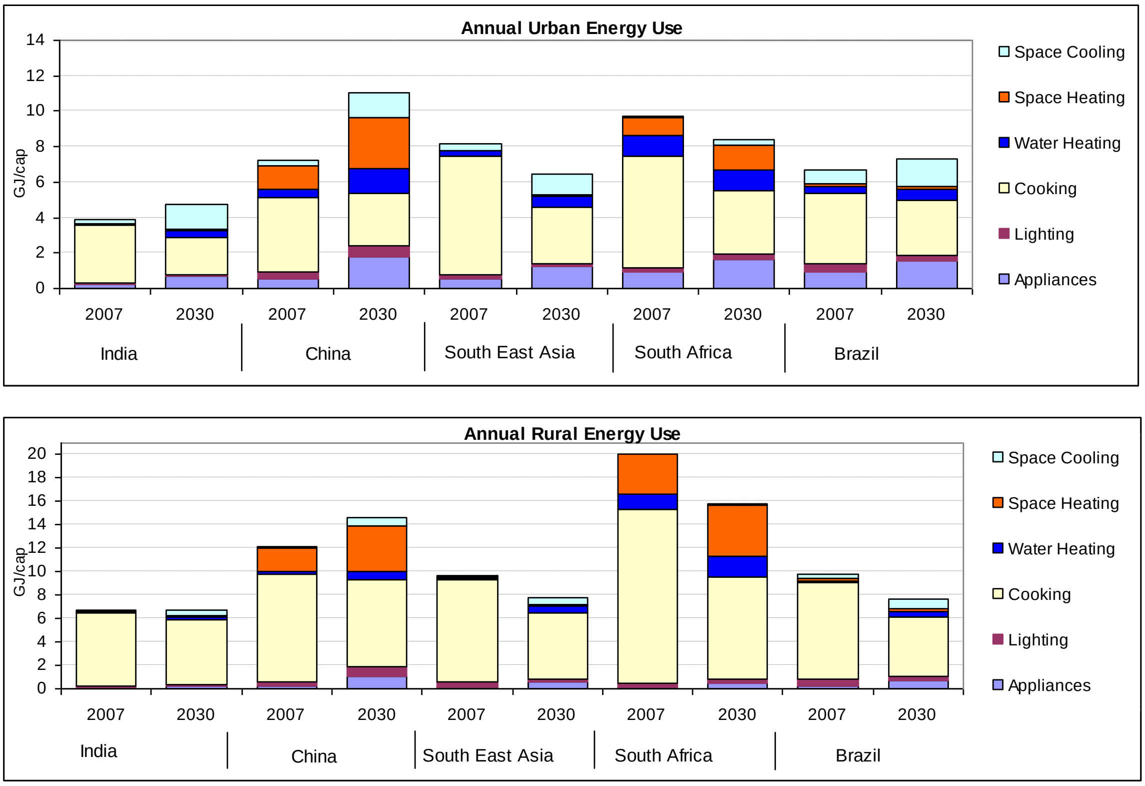


Figure 2. Annual final energy use per capita (GJ_{SE}/cap) by end-use function, urban (upper) and rural (lower) areas.

Figure 3 shows the total final energy use per capita by energy carrier. As can be seen, traditional fuels hold a large share in the final energy use of all regions looked at in this paper, especially in 2007 and in rural areas. With increasing income levels, the model shows that households switch towards cleaner (and more efficient) fuels. In several, cases this even reduces the total per capita energy consumption: This is the case for rural households in all regions except China where the large increase in space heating energy demand results in a net increase of the overall demand. Furthermore, China and South Africa are the only regions which show a significant use of coal (especially for rural households) as it represents a cheap and abundant supply in these regions.

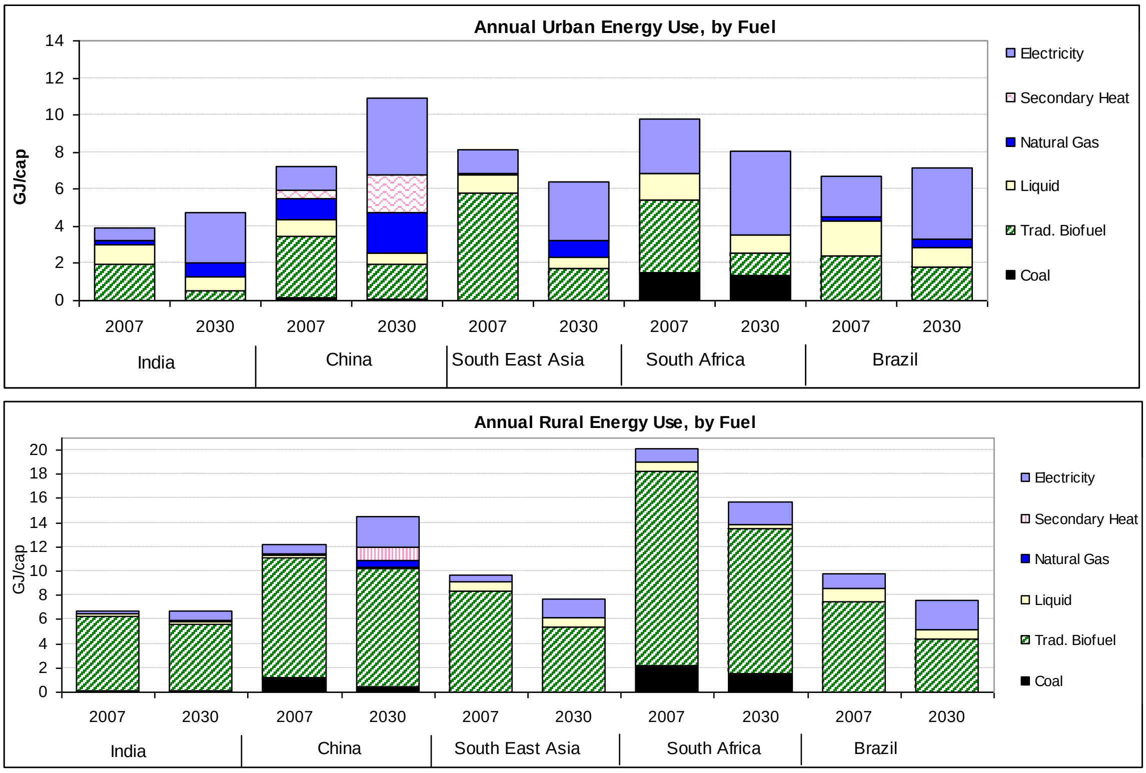
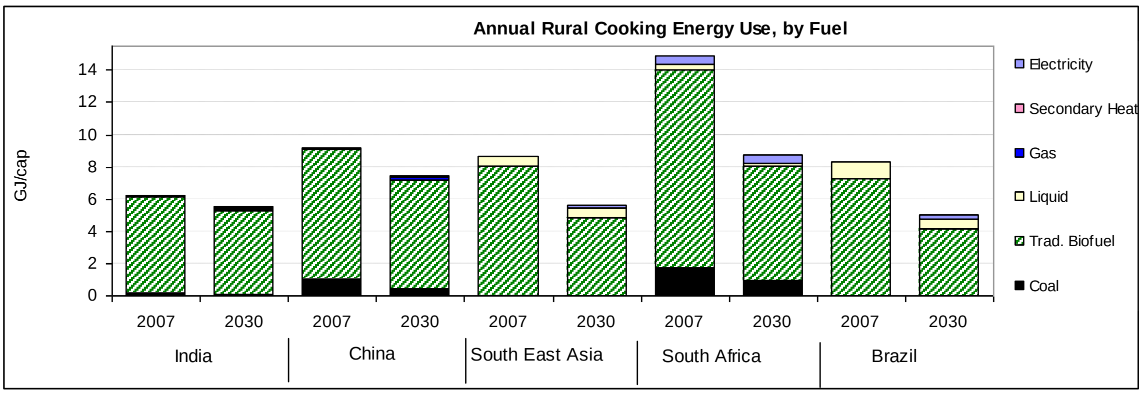


Figure 3. Annual final energy use per capita (GJ_{SE}/cap) by fuel, urban (upper) and rural (lower) areas.

The projected 2030 per capita energy consumption levels in Figure 3 range from 4 to 20 $GJ_{SE/cap}$,. Households in the USA, however, currently consume about 45GJ_{SE}/ (about half of this is for space and water heating) indicating that even in 2030 there is a huge potential for further increase in energy use. The countries we analyze do not reach such high levels of energy demand even amongst the richest cohort, partly as a result of climatic differences, but also due to lower household expenditures. Energy use of OECD regions are not predicted to change much in the studied time frame (IEA, 2010b; Kyle, Clarke, Rong, & Smith, 2010).

Cooking and Heating

The projected use of energy for cooking is detailed further in Figure 4. The supply of cooking energy use is dominated by traditional fuels, especially in rural areas. The demand for cooking energy falls for both urban and rural households due to fuel switching, which leads to the use of more efficient fuels, as well as autonomous increases in efficiency for any given fuel.



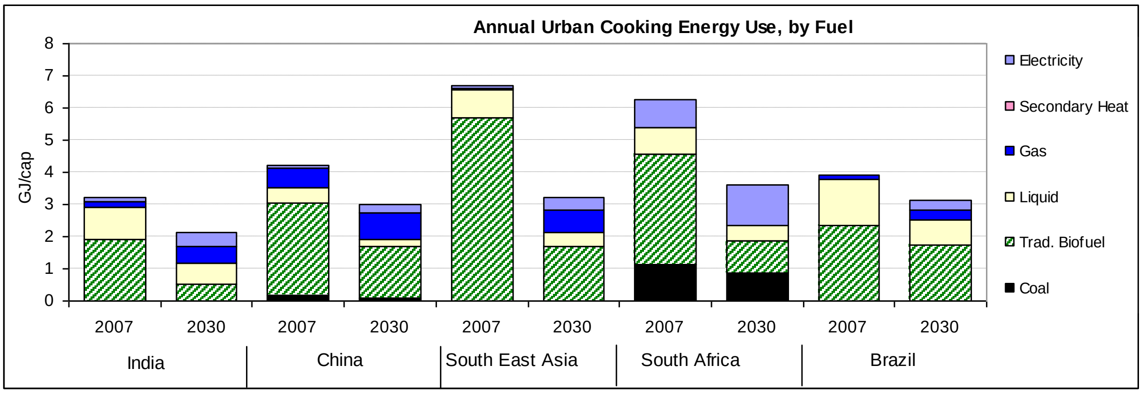


Figure 4. Annual final energy use per capita (GJ_{SE}/cap) for cooking by fuel, urban (upper) rural (lower) areas.

Figure 5 shows the cooking capital for urban and rural households per quintile for India. This nicely illustrates the transition from traditional to modern fuel across the different income quintiles. For the lowest rural quintiles (R1 and R2), almost no changes are projected between 2007 and 2030: at the same time, very significant changes occur for the cohorts R3, R4, R5, U1 and U2. This implies that inequality and poverty also play a key role in the fulfilment of energy functions. Poverty can act as a significant barrier to fuel switching leading to a situation in which the poorest households only meet the basic functions using solid fuels. Furthermore, it can be seen that also LPG and kerosene are in the long-run replaced by natural gas and to a lesser extent, electricity.

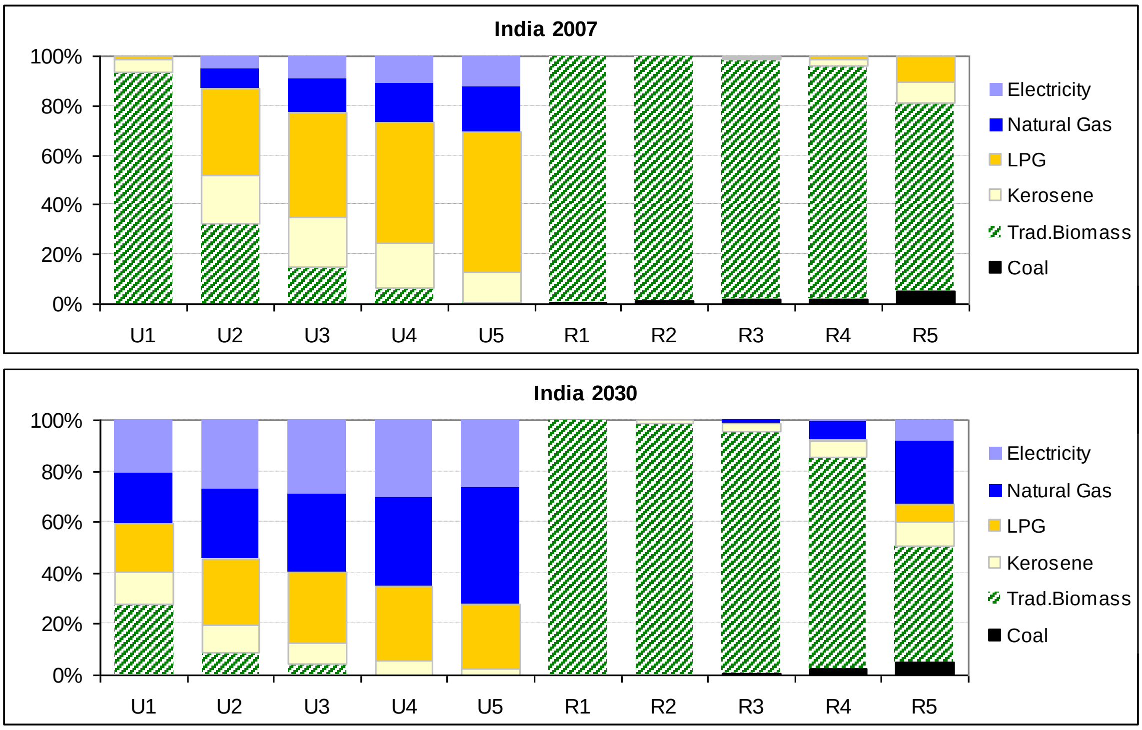


Figure 5. Shares of cooking capital in India in 2007 (upper) and in 2030 (lower), urban/rural quintiles.

The demand for heating is driven by climate factors and household expenditures. Figure 6 shows the space and water heating energy use per capita by fuel. As can be seen, increases in heating demand in rural India, South East Asia and South Africa are primarily met by increased use of traditional biomass. This is not true in the more prosperous urban households. In urban China, the model assumes that secondary heat becomes the dominant heating fuel (the underlying energy system calculation shows that natural gas is only available through major imports making it a less favored choice). South Africa is the only region which currently uses significant amounts of electricity to meet both cooking and heating functions. It is projected that this situation does not change. The projections show, finally, that gaseous and liquid fuels dominate urban India, South East Asia and Brazil.

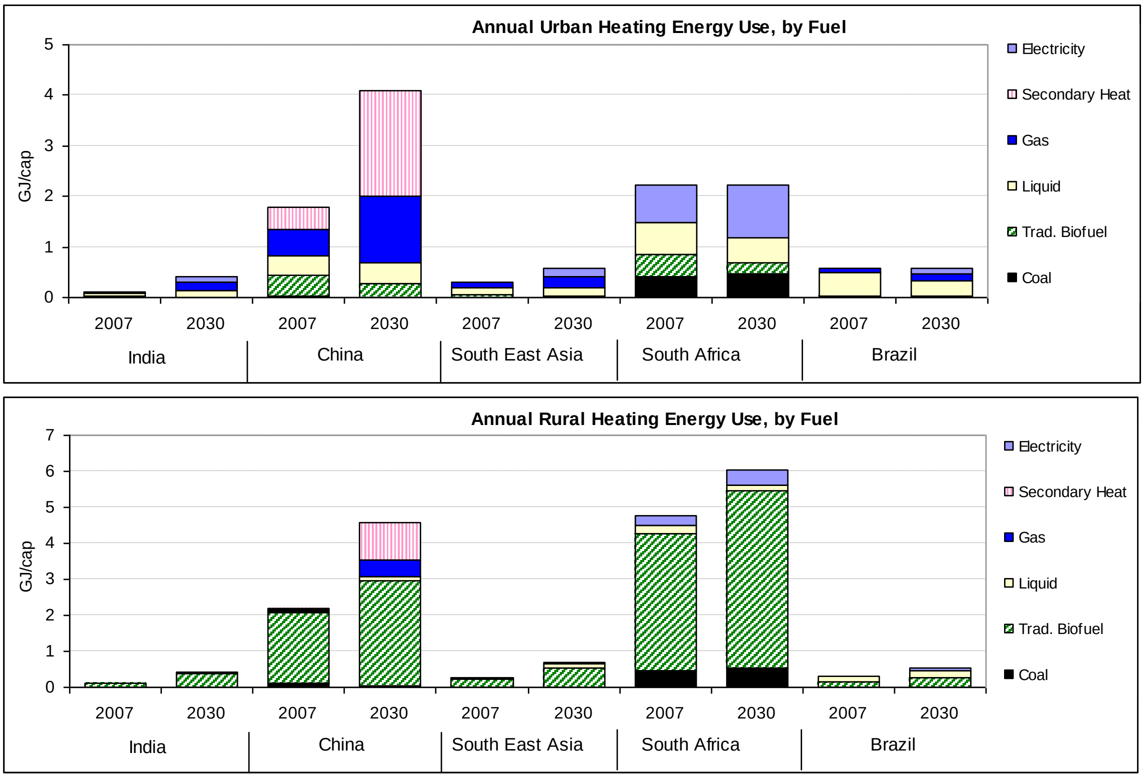
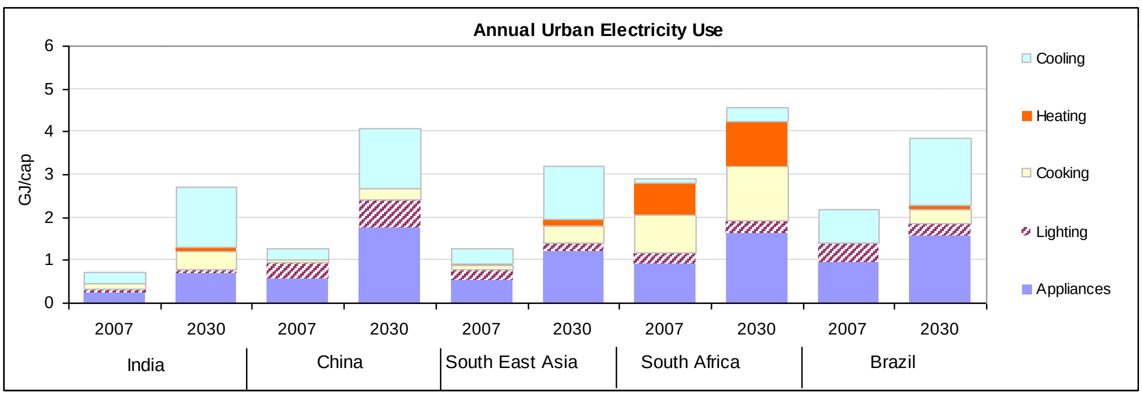


Figure 6. Annual final energy use per capita (GJ_{SE}/cap) for space and water heating by fuel, urban (upper) and rural (lower) areas.

Electricity Use

Figure 7 shows the residential use of electricity by end use functions. The projection expects electricity use to increase in all regions for both urban and rural populations. The increase is mainly attributed to appliances and cooling but also cooking in (due to fuel switching) and heating in South Africa as heating demand grows (as already mentioned, South Africa already has a high use of electricity for heating). In rural households, electricity use is projected to remain significantly lower that urban areas due to lower expenditures and lower electrification rates.



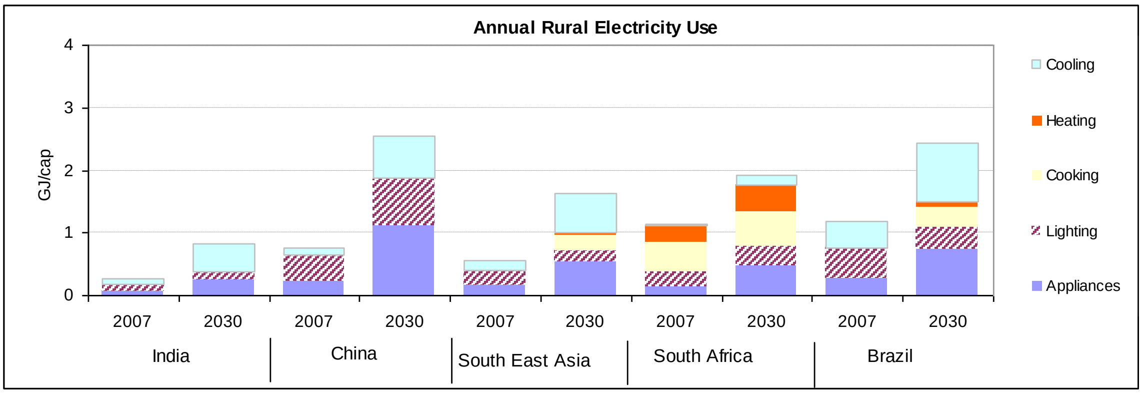


Figure 7. Annual electricity use per capita (GJ/cap) by function, urban (upper) and rural (lower) areas.

2.4. Residential sector: Baseline Energy Demand projection for Intergrated Assessment modeling in REMIND

Authors: Antoine Levesque, Michaja Pehl, Christoph Bertram, Gunnar Luderer – Potsdam Institute for Climate Impact Research

Introduction

The REMIND model (Luderer, Leimbach, et al. 2013) has been applied successfully to analyze a series of energy-related issues.(Luderer, Pietzcker, et al. 2013), for instance, studied the issue of postponing mitigation policies and found that delaying action closed the door to stringent climate targets. (Bertram et al. 2015) showed how early second-best mitigation policies could help keeping ambitious climate targets within reach. Yet, the REMIND model still contains a coarse representation of demand side efficiency improvements. This shortcoming prevents it from assessing policy mixes with explicit energy efficiency policies for different sectors, even though many institutions have already rolled out efficiency improvement policies. As an example, the European Commission passed two directives in 2010 and 2012 which plan that each new building constructed from 2020 on should meet nearly zero energy building standards. In order to improve the demand-side representation, the REMIND model is currently undergoing fundamental developments, some of which have already been completed.

In the following, we present a multiple step approach that aims at enhancing REMIND's energy efficiency dynamics. The first stage delegates the construction of baseline final energy demand to the model EDGE (*E*nergy *D*emand *GE*nerator). In a second step, the macro-economic production function of the REMIND model is then calibrated to match these projections in a baseline scenario. This approach based on EDGE, a relatively simple econometric model combined with long-term convergence assumptions, helps reproducing historic trends and stylized facts and provides simple insights to the baseline energy demand trajectories. Finally, the dynamics of efficiency gains investments, as part of a mitigation policy, are included as a stylized trade-off between capital and energy consumption. The current status of REMIND represents this trade-off at the aggregated, economy-wide level. In order to better capture the sectoral specific potential of energy efficiency, we modify the structure of REMIND.

The rationale for this multiple step methodology, instead of relying only on REMIND, lies in the difficulty of providing reasonable baseline projections with intertemporal general equilibrium models, such as MERGE(Manne, Mendelsohn, and Richels 1995), REMIND or WITCH(Bosetti et al. 2009). In these models, final energy demand emerges from the macro-economic production function, usually a constant elasticity of substitution (CES) function. In this setting, the temporal evolution of various final energy demands is essentially driven by efficiency parameters in the production function, which cannot be observed in the real world and thus lack an empirical foundation. Relying on ad-hoc assumptions for these efficiency parameters also has the drawback that underlying driving mechanisms may be hard to understand.

Construction of baseline final energy pathways

EDGE relies on a mixture of econometric projections and convergence assumptions to produce baseline energy demand projections. The econometric projections play an important role in the short run while convergence assumptions rather influence the longer run.

In the econometric part, projections are derived for different energy carriers in several economic sectors (residential, commercial, industry, agriculture and fishery, other, non-energy use). The regressions draws on the historical relationship between the per capita energy carrier demand in each given sector and the GDP or sectoral value added per capita. The specification of the econometric model differs from one energy carrier to the other depending upon the observed relationship in historical data between the explained and the explanatory variables, or upon the regional heterogeneity. Each sectoral energy carrier is treated individually, which allows for a better control of the econometric fit, but has the disadvantage of ignoring the interdependencies between them. However, these interdependencies are partly reflected in the historical data.

The coefficient estimates from the econometric regression are used for projecting the final energy demand trajectories. One of the most important criteria for the functional form of the econometric model is the compliance of the projection results with energy stylized facts (see below).

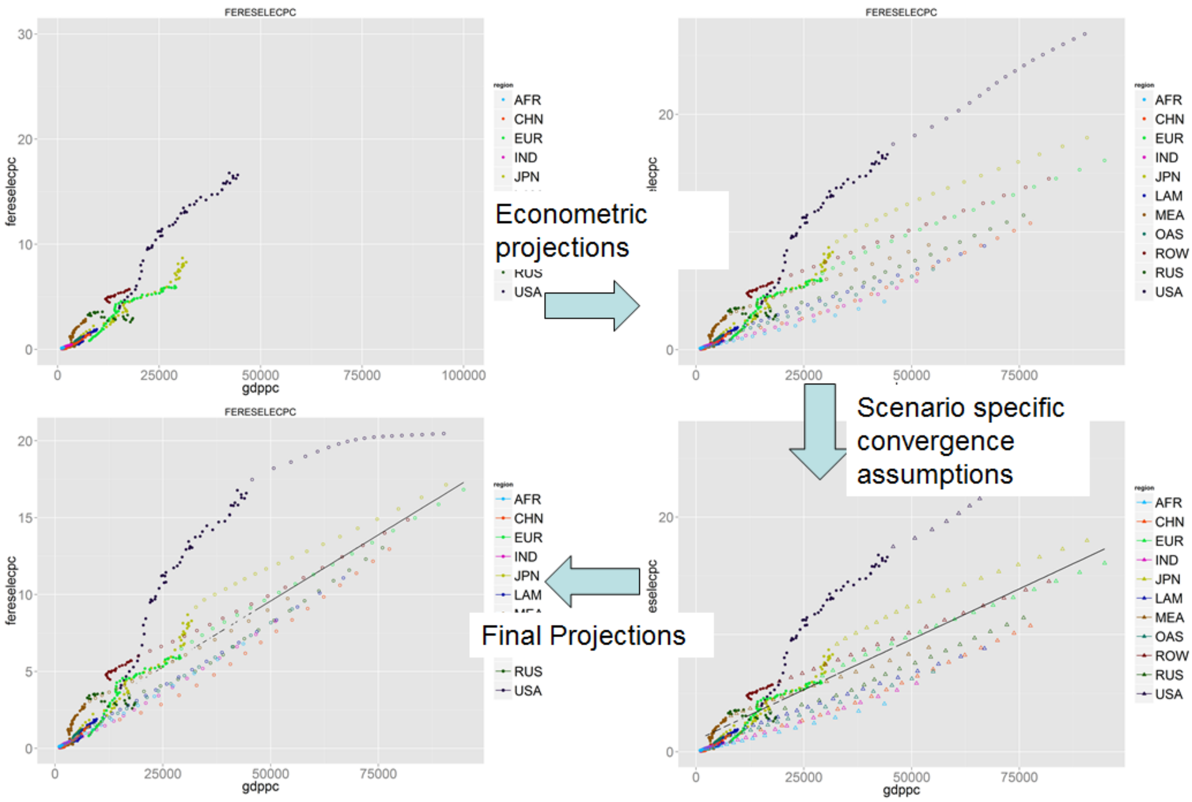


Figure 8 Methodology for the construction of final energy projections.

In the convergence part, a global convergence line is first computed, which relates the per capita demand for the energy carrier and the per capita value added level. Each region is then assumed to converge towards this line in the long term (without necessarily reaching full convergence within the time horizon of the model). The convergence assumption differs across energy carriers and sectors. Typically, demand for electricity will assume greater convergence than demand for gas, liquids or district heat.

This methodology allows for substantial flexibility in the drivers to be taken into account, as well as in the variables to project. Many variables can be included to the regressions, which play an important role for the baseline case, but would not necessarily be expected to change significantly under climate policy, such as the demand for floor space. Also, this methodology allows a sectoral disaggregation that goes beyond the one available within the REMIND intertemporal optimization framework. This approach can be useful for post-processing of REMIND results by providing a sectorial disaggregation key.

The resulting projections depicted in Figures 2 and 3[4] show agreement with several energy stylized facts(van Ruijven et al. 2008). In line with the energy-ladder concept(Karekezi et al. 2012), the share of solids decreases widely, most notably due to the phase-out of traditional biomass in developing countries. By contrast, the share of grid-based energy carriers, in particular electricity, is projected to increase across all regions over the century. Following GDP per capita and population projections, developing regions' demands grow fast, while developed regions experience a slower increase. In line with other studies, we find that currently least-developed countries will account for the bulk of global energy demand in the long-term[5].

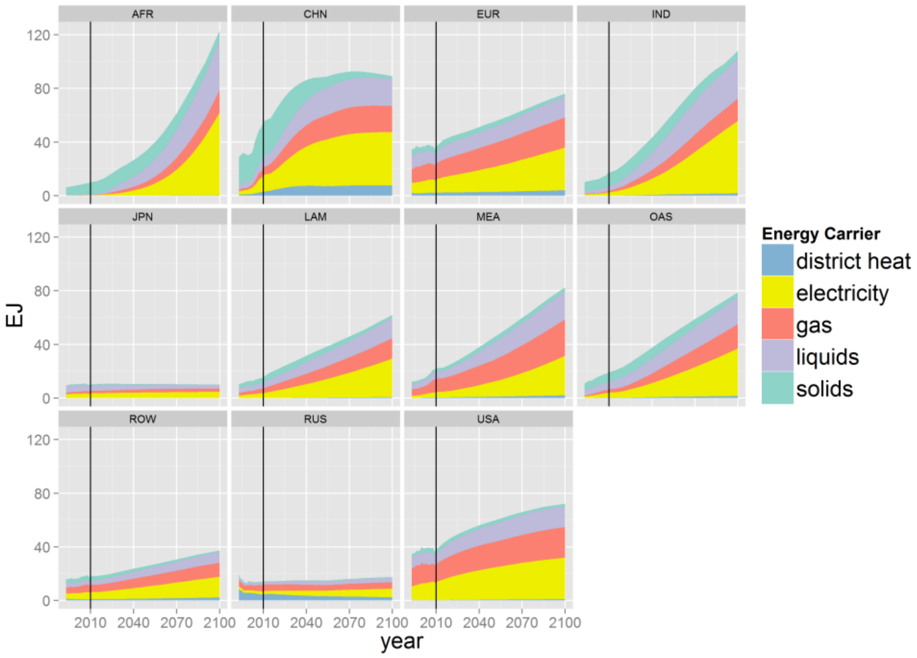


Figure 9: Results - Regional final energy projections by energy carrier.

[4] The energy carriers depicted on the figures have been aggregated to the final energy carriers categories of REMIND. EDGE also represents traditional biomass, modern biomass and coal for certain sectors. Therefore, it is possible to make statements on the use of traditional biomass with the results of EDGE.

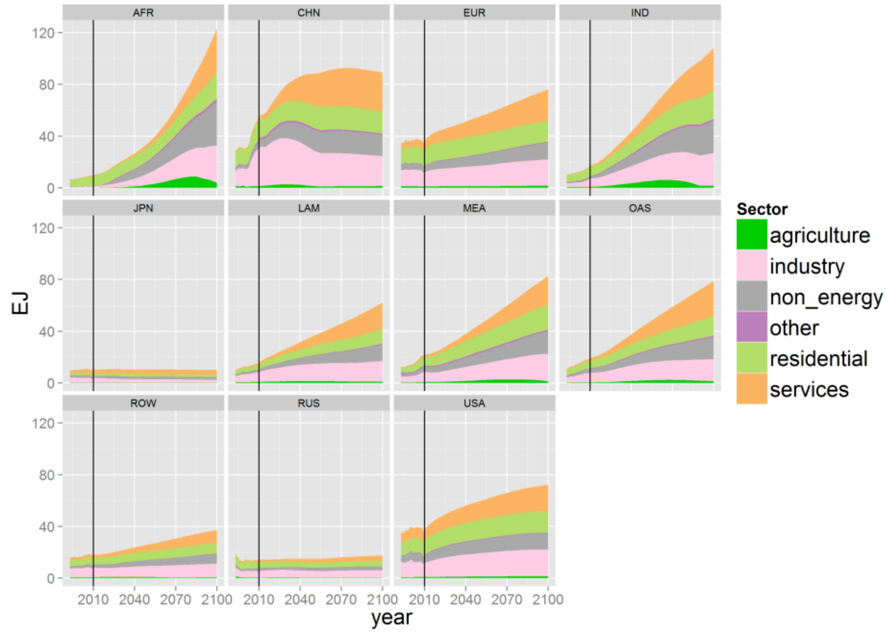


Figure 10: Results - Regional final energy projections by sector.

Calibration of REMIND

Once these projections are constructed, they are aggregated to the sectoral and energy carrier levels present in REMIND. Residential and commercial buildings are thereby lumped together. Then, the CES production function of REMIND is calibrated to these energy demand pathways by adjusting the efficiency parameters at each CES level in each time step.

The adjustment of the CES parameters is an iterative process. From the quantities calculated with EDGE, the energy prices from REMIND and the general CES structure, the efficiency parameters at each CES level are calculated. Then, a new REMIND scenario is generated using the new efficiencies. With the updated prices from the new run, the efficiency calculation is performed again. This process is repeated until convergence.

Below, we depict some figures comparing the REMIND results and the EDGE input data. Even though a full agreement between both is not achieved, the matching reaches a satisfying level.

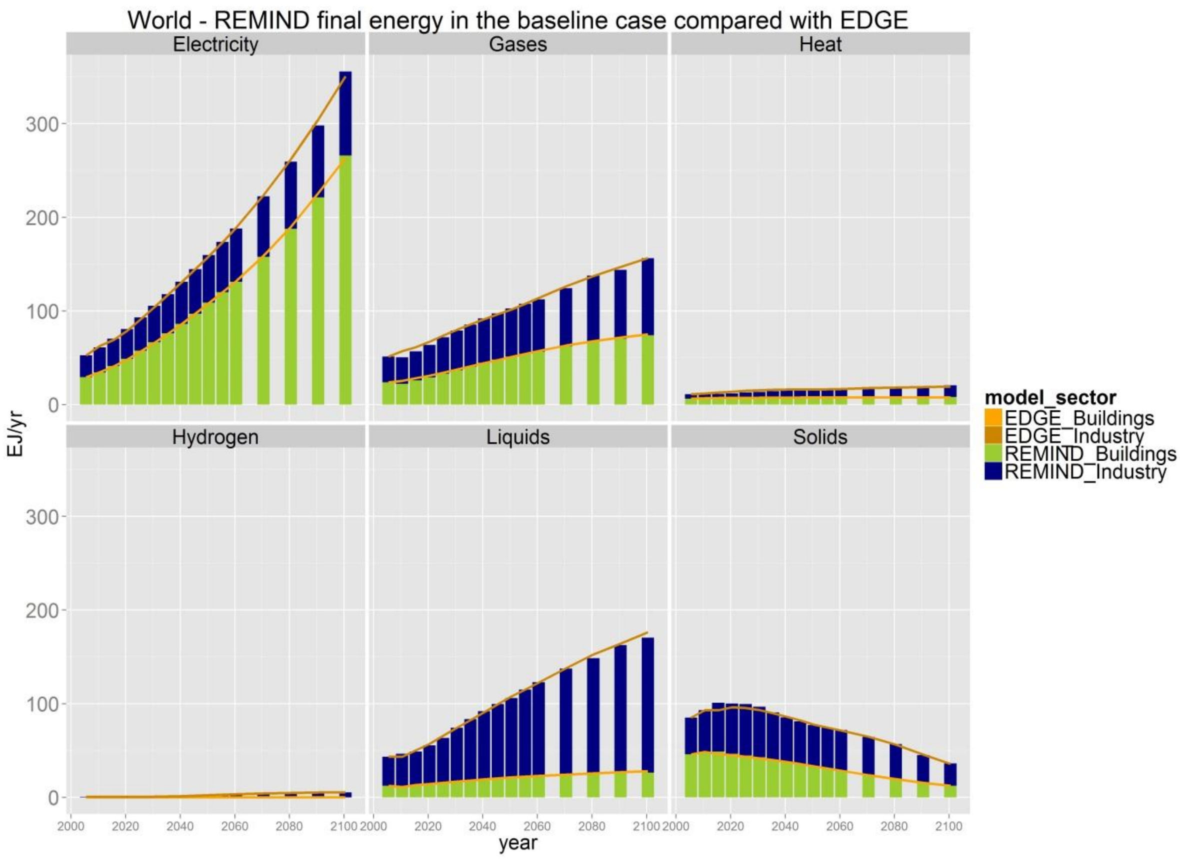


Figure 11: Comparison of the aggregated EDGE trajectories and REMIND results for several energy carriers.

Energy Efficiency Potential

After having explained the calibration of the model to exogenous baseline final energy trajectories, we briefly describe the planned model developments aiming at representing energy efficiency policies. The potential for energy efficiency improvements in buildings is not explicitly implemented in the model yet. At the current stage of development, energy efficiency on the demand side can only be raised by substituting capital stock for energy at the aggregated economy-wide level. Hence, the efficiency improvements in buildings cannot be split apart from energy efficiency improvements in every other economic sector.

The coming step in model development is to integrate a sectoral specific representation of energy efficiency improvements. The underlying idea is that the substitutability between energy-specific capital and energy consumption for providing a given amount of energy service differ in the different energy sectors: increasing the efficiency of lighting by exchanging light bulbs with LEDs can have very different capital requirements compared to increasing the efficiency of a house by improving the insulation. By including explicit capital stocks with different substitution elasticities for the provision of different energy services in the buildings sector (space conditioning, water heating, cooking, appliances), REMIND would better represent the driving mechanism behind energy efficiency improvements. Some effort has already been done in computing elasticities of substitution for such trade-offs(MK Jaccard and Associates Inc and Navius research 2013). Other references could constitute a valuable input for computing them(Ürge-Vorsatz et al., n.d.).

Conclusion

The approach adopted with REMIND in order to better model future energy demand and study the potential of energy efficiency improvements follows hence several steps. These steps encompass the calculation of baseline energy demand trajectories with an external model, EDGE, and the calibration of REMIND to these trajectories. This enables to bypass some drawbacks of intertemporal general equilibrium models whose baseline projections otherwise heavily depend on ad-hoc assumptions about intangible efficiency parameters. The proper assessment of mitigation potential resting in efficiency improvements constitutes a related but distinct development. A stylized substitution relationship between capital and energy consumption at the sectoral level is envisioned to better capture the driving mechanism underlying efficiency improvements. To that end, the macroeconomic module of REMIND will be reshaped.

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2.5. Residential sector: POLES model

Author: Alban Kitous, European Commission – JRC IPTS

The representation of the residential sector has been improved in the course of the ADVANCE project WP2. What follows is a description of the end uses modelled explicitly in the POLES model and how they relate to the POLES drivers.

The evolution of energy demand is related to the evolution of the building stock, which differentiates existing, renovated and new surfaces:

- new surface = f(population, income, size of household);
- five energy services described : space heating, space cooling, water heating, cooking, lighting & appliances (vs. two only in the pre-ADVANCE version: lighting & appliances, other usage);
- insulation penetration = f(savings on space heating and space cooling, renovated surface, new surface);
- competition across fuels is based on cost for user (fuel price, equipment costs, efficiency).

1. **Space heating** depends on:
- the surface;
- the energy cost for consumer of different options (electrical heater, gas, oil, biomass, coal, solar);
- HDD evolution (elasticity 1.1);
- building insulation (better performance of new buildings vs. renovated buildings).

2. **Space cooling** is the product of the penetration of equipment and of the unit consumption moderated by the efficiency:
- Penetration of equipment (*Isaac 2009*):

$$\text{Max penetration}_{CDD} * \text{diffusion}_{\text{Income per capita}}$$

$$\text{Max penetration} = 1 - 0.949 * e^{(-0.00187*CDD)}$$

$$\text{Diffusion} = 1 / (1 + e^{(4.152)} * e^{(-0.237 * \text{Income pc})})$$

- Unit energy consumption per dwelling equipped (*our own estimate*):

5.13*GDPPOP[ALLC] + 0.0621*CDD[ALLC]*GDPPOP[ALLC] - 1657.94

- Efficiency of the cooling system depends on:
  - *in existing equipment*:
    - building insulation (better performance of new vs. renovated);
    - price effect (behavior);
  - *in new equipment*:
    - building insulation (better performance in new vs. renovated);
    - price effect (behavior);
    - technological progress: autonomous trend influenced by:
      - spending on cooling,
      - Floor = 20% best UEC / CDD / m2 in 2010.

3. Energy demand in **water heating** and **cooking** depends on income and energy price evolution, with a competition across fuels depending on each fuel cost for the user.

4. Electricity demand for **lighting & appliances** depends on income and electricity price evolution.

2.6. Service sector: Example of modelling demand drivers in IMAGE[6]

Authors: J. Fleischman, O. Edelenbosch, V. Daioglou, D.P. van Vuuren – PBL Netherlands Enviromental Assessment Agency

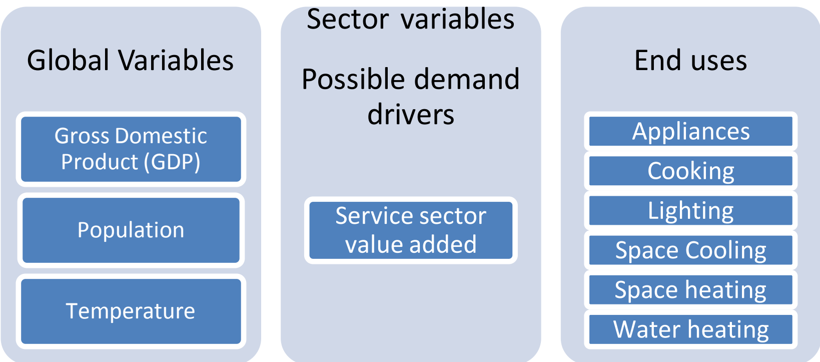
The service sector, also referred to as the commercial and public service sector, or the tertiary sector, has grown rapidly in the last decades, resulting on an increase of final energy consumption of 37% between 1990 and 2005. In 2005 the final energy consumption was 27 EJ, and the associated CO_2 emissions, including indirect emissions from electricity, amounted to 2.6 GT CO_2. 73% of the service sector final energy demand is consumed in the OECD; however energy use has grown faster in Non-OECD countries recently (IEA, 2008).

The growth of service sector final energy consumption is mainly due to an increase in electricity use, which has grown by 73% between 1990 and 2005. The use of electricity driven devices such as lighting, air conditioning and electric appliances have become more important in the last years. The service sector energy mix varies significantly amongst countries. Natural gas and electricity are the dominant energy carriers in most OECD countries, while China and South Africa use a significant amount of coal, and India relies mainly on both coal and biomass (IEA, 2008).

The service sector comprises a wide range of activities, including trade, finance, real estate, public administration, health, food and lodging, education and commercial activities[7]. These activities serve different purposes and therefore require different technologies. This is reflected in their heterogenic demand for energy end uses. The heterogeneity of the service sector in activity and end-uses makes analyzing the development of its energy consumption and CO_2 emissions a challenging task, and requires detailed disaggregated data. As the service sector energy demand is growing, with increasing emissions affecting climate change, it has become more important to understand what drives the sector's energy demand.

Within the ADVANCE project a detailed service sector model has been developed, containing a representation of service sector energy demand drivers and its end-use structure. The main drivers of service sector energy demand have been identified, by taking a closer look at the regional service sector end-use demand. By modelling energy end uses the sectors' behavior in terms of structural change of end-uses, energy intensity and technology change can be represented. Figure 1.1 shows the proposed disaggregation of the sector by end-uses and the demand drivers to be used in the model.

Figure 1.12 Data, end-uses and demand drivers for the service sector model



The research was carried within the Integrated Model to Assess the Global Environment (IMAGE) and The IMage Energy Regional Model (TIMER). IMAGE is an ecological-environmental model framework,

[6] This section is part of ongoing research planned to be submitted to a peer reviewed journal.
[7] As classified by the International Standard Industrial Classification ISIC two-digit level rev. 4.0 – 33, 36-39, 45-96, 99 excluding class 8422 (UNSD, 2008).

developed by PBL Netherlands Environmental Assessment Agency, which simulates the environmental consequences of human activities worldwide. To represent global energy supply and demand, an energy-system simulation model, TIMER, has been integrated into the IMAGE model. TIMER simulates trends in energy use and efficiency, and is used to analyze long-term energy demand and supply scenarios in the context of sustainable development challenges (Van Vuuren et al., 2014).

Modelling method: Relating service sector energy demand to drivers

A literature research for service sector energy demand data was conducted collecting data from several countries (Brazil, China, South Africa, United Kingdom, United States of America, and Canada). The different datasets were difficult compare due to incompatible timeframes and varying definition of the end-uses. The IEA provided service sector data for 25 regions per end use and energy carrier in 2011. Even though this data does not have a time dimension, it contains consistent and detailed data with high global coverage, originating from a reliable source.

Based on the IEA data relations between scenario drivers and service sectors energy end use have been formulated. Figures 2.2-4 show the amount of useful energy demand per capita for each region's level of SVA, for Appliances, Lighting and Space Cooling. Figures 2.5-7 show the amount of useful energy demand per capita per degree-day for each region's level of SVA for the end-uses Cooking, Space Heating and Water Heating, that depend on temperature differences[8].

It can be seen that countries with a higher SVA per capita present higher UE demand per capita and countries with low SVA per capita use less energy, suggesting that there is a relation between the energy demand of the sector and its economic activity. The Gompertz function (eq. 1) is used to represent this behavior. In the appendix the outcome of the regression analysis can be found.

Equation Gompertz function

$$y\ x\ = ae^{-be^{-cx}} \qquad (1)$$

where:

- a = asymptote, sets the carrying capacity
- b = displacement along the x axis, positive number
- c = growth rate
- *e* = Euler's number

Appliances, Lighting and Space cooling are generally speaking, only fueled by electricity, which results in a straightforward conversion to Final Energy. Cooking, Space heating and Water heating can be fueled by different energy carriers, which involve different conversion efficiencies. For these functions the conversion to Final Energy depends on the shares of each energy carriers. The energy carrier market shares vary among regions, depending on fuel prices and availability, and also on technological preferences (e.g., in some regions electrical water heaters are more common that gas water boilers). In TIMER the multinomial logit function (MNL) is used to determine the market share of the different energy carriers based on their relative fuel prices in a set of competing energy carriers and taking fuel-specific conversion efficiencies into account (eq. 2)

Equation Multinomial Logit

$$MS_{R,EU,EC} = e^{-\lambda c_{R,EC}} \quad {}_{EC}\, e^{-\lambda c_{R,EC}} \qquad (2)$$

Where:

[8] The final energy data was converted to Useful Energy, using the global conversion efficiencies for each energy carrier

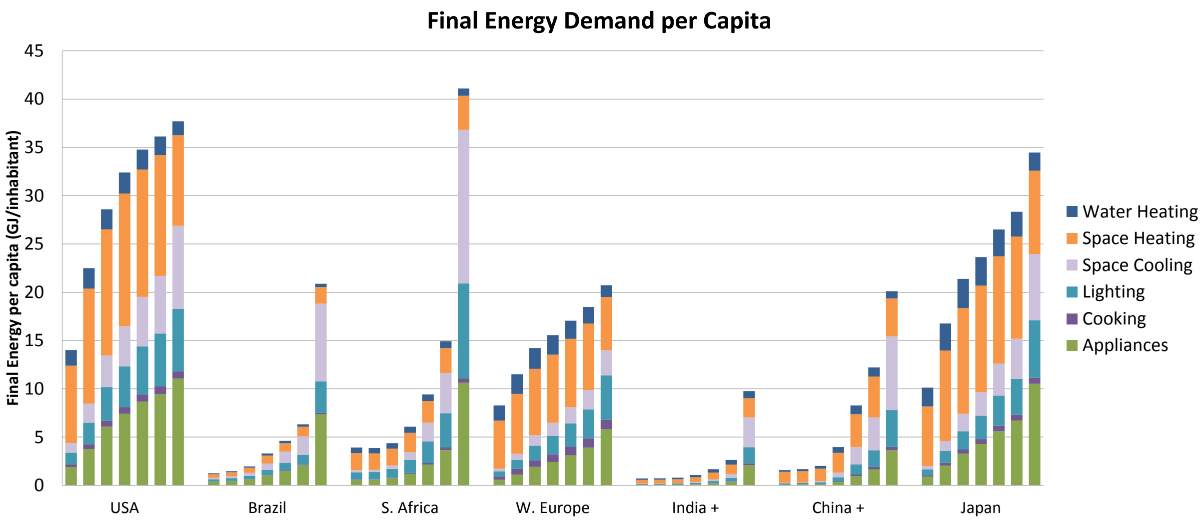
- MS = Market Share
- R = TIMER region
- EU = Energy End Use
- EC = Secondary Energy Carrier
- λ = Logit factor, substitution sensitivity to fuel costs
- c = Fuel costs

The fuel costs are endogenously calculated in the TIMER supply module taking direct production costs and energy and carbon taxes into consideration.

Baseline final energy demand

The new service sector model results are tested using SSP2[9] scenario assumptions. In SSP2 SVA per capita is assumed to increase until 2100 in all regions as SVA grows at a higher rate than population. Therefore, energy use per capita continues to increase throughout the century as can be seen in Figure 2.13 Final energy demand per capita. Model results for USA**, Brazil, South Africa, Western Europe, India, China and Japan, disaggregated by end-uses for the years 1975, 1990, 2005, 2020, 2035, 2050 and 2100.**. Figure 2.14 shows the projected development of final energy demand by end-use. The results are presented for the years 1975, 1990, 2005, 2020, 2035, 2050 and 2100, and for seven TIMER regions. These regions were chosen for their importance in world economy and their varied temperatures.

Figure 2.13 Final energy demand per capita. Model results for USA, Brazil, South Africa, Western Europe, India, China and Japan, disaggregated by end-uses for the years 1975, 1990, 2005, 2020, 2035, 2050 and 2100.



Globally, space heating is responsible for the largest share of service sector energy use. Per region, however, this depends on regional climate characteristics (HDD). This is the reason why in Brazil, a

- [9] SSP2 is the middle of the road scenario. It depicts a future where the development trends do not shift markedly towards any direction, and are consistent with the historic growth patterns. Environmental systems keep degrading; meanwhile, technology improves without major breakthroughs. Fossil fuel dependency declines gradually, but no policy framework boosts the use of renewable sources or sets limits to the use of unconventional fossil resources. Population growth is moderate and it levels off by the second half of the century (O'Neill et al., 2015).

very warm country with low HDD, space heating takes up a relatively small share. Furthermore, it can be seen that space cooling share starts to increase rapidly after a certain SVA per capita level, i.e. China, where Space Cooling has a very small share until after 2020, and in 2050 it has a share comparable to that of Space Heating. Cooking for all regions and time takes up the smallest share.

It is worth noting that among regions with similar SVA per capita there are significant differences in the final energy demand. This is evident when comparing Japan to the USA and Europe, or Brazil to India and China. This is mainly because of differences in the fuel mix, and thus the efficiency of meeting the useful energy, but also due to a different end-use structure. The structure of end-uses in the service sector has a region specific energy matrix that will depend on the availability of the energy carrier, its cost, and the technological preference of the region.

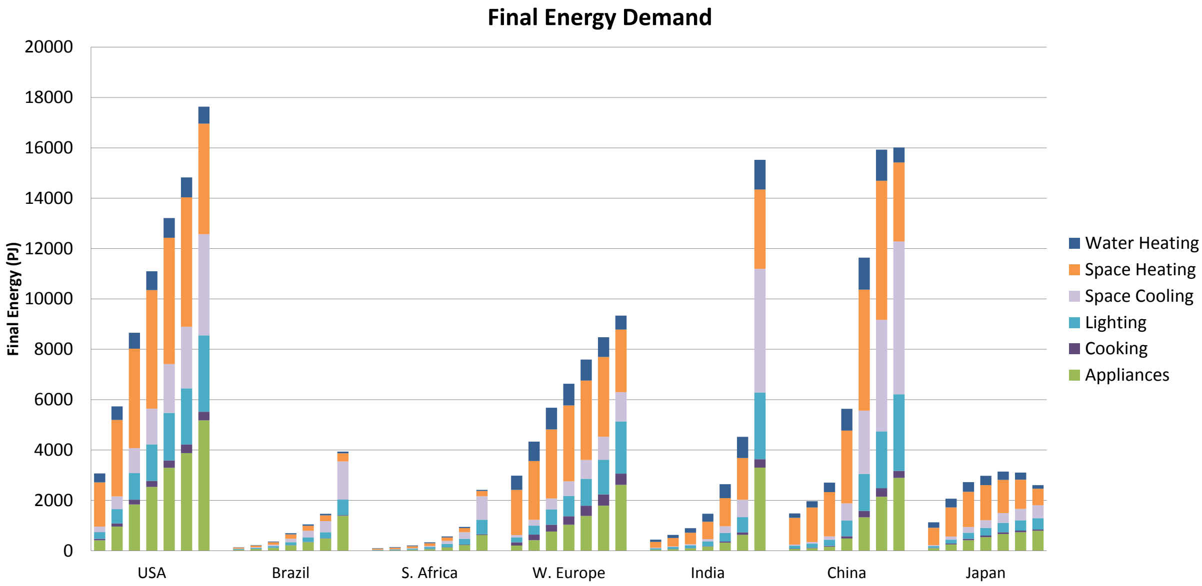


Figure 2.14 Final energy demand. Model results for USA, Brazil, South Africa, Western Europe, India, China and Japan, disaggregated by end-uses for the years 1975, 1990, 2005, 2020, 2035, 2050 and 2100.

Figure 2.15 shows the share of each of the secondary energy carriers involved in the service sector. The new model projects a tendency towards electrification in the service sector. This is due to: a) the increasing share of Appliances (from 15,8% in 2010 to 25,1% in 2100, global), Lighting (11.3% to 16.4%) and Space Cooling (9.2% to 32,6%) in the sector's structure, with the latter becoming the more important energy end-use of the service sector by the end of the century, and, b) the price increase of fossil fuels, which makes the MNL function of the model to choose less expensive and more efficient energy carriers, such as electricity.

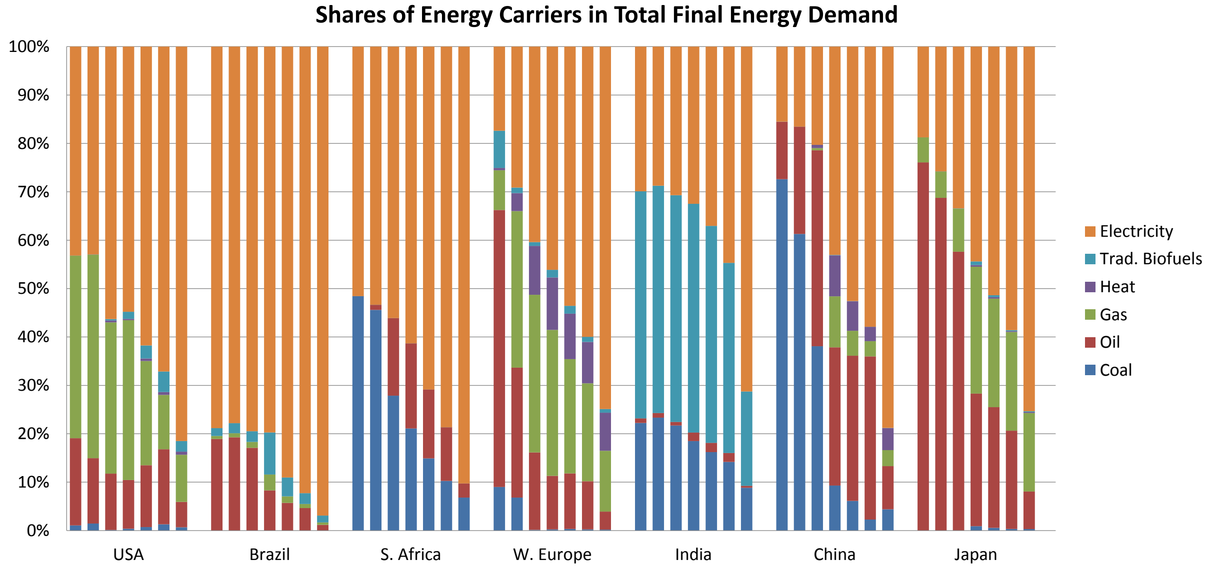


Figure 2.15 Market shares of the different energy carriers. Model results for USA, Brazil, South Africa, Western Europe, India, China and Japan, for the years 1975, 1990, 2005, 2020, 2035, 2050 and 2100.

Discussion and Conclusion

The service sector model was developed based under the assumption that regions follow the same development in service sector energy end use, corrected for climate conditions. This assumption had to be made as comparable data was only available for 2011. It could be argued however that each region has a different service sector activity structure, therefore different paths of development.

Further research could be improved by a) developing different functions for different groups of regions depending on their level of service sector development, b) compile more information of the service sector by region, such as:

1. Floor area – This would allow a better modeling of the upper limits of functions as space heating, space cooling and lighting and efficiency improvements.
2. Number of employees – This model was constructed by linking SVApc to UE per inhabitant. If the SVA increases but less people work in the sector this could lead to decreasing demand of for example space heating demand, which currently is not taken in to account.
3. Building stock – In order to improve the potential and barriers to efficiency improvements in the service sector the building stock can be helpful. In addition information on energy efficiency measures in building codes and regulations can be included.
4. Share of the different activities – The service sector consists of many different activities: from hospitals to schools, office buildings to casinos, IT buildings, shopping malls and supermarkets, hotels and restaurants, that all differ in demand of energy requiring uses.

The previous model included factors to represent two types of energy efficiency improvement: autonomous energy efficiency improvement (AEEI) and price-induced energy efficiency improvement (PIEEI).

AEEI is implicit in the Gompertz function where after a certain level of SVApc, UE demand growth decreases. This based on the assumption that countries get more efficient as their SVA grows.

PIEEI has not been modeled, as the price of fuel does not represent a reason for switching towards more efficient conversion technology. Research shows that several barriers for the service sector to improve its efficiency can be found in many of its sub-sectors. As described by Schleich, J., & Gruber,

E. (2008), the energy cost share in this sector is in most cases very low (3% share in total turnover), in contrast with energy-intensive industries for example. This leads to a certain unattractiveness of the energy efficiency investments, mainly due to for example: a) considerable uncertainty on the amount of energy savings, therefore return of investment, due to a lack of energy use measurement, b) hidden costs (time and resources) for information gathering about the different energy efficiency measures, or technologies, or c) the investor/user dilemma, when companies work on rented spaces, and neither the landlord nor the tenant possess a real incentive to invest in energy efficiency, as no matter who invests, they will not be able to fully appropriate the benefits. Therefore energy saving, or cost saving energy-related projects have low chance in competing with core-business cost-saving projects in the service sector. Literature has also shown that energy efficiency improvement in the service sector is achieved when it is induced by new policies, e.g. with new building codes, lighting efficiency and energy-efficient appliances regulations, which can even imply getting more efficient cooking, space and water heating, and cooling technologies (Schleich, 2008). Thus, it is recommended to improve the model by modeling a policy-induced energy efficiency improvement.

An example of this can be found in the modelling of lighting. Lighting requirements for working spaces are established in lumens per square meter or lux. According to the European standard, BS EN 12464-1:2011, office spaces require a minimum of 300 to 500 lux, depending on the task to perform. Similar work place lighting standards can be found in several regions. Lighting fixtures, e.g. fluorescent lamps, output a certain amount of lumens per watt of input; this is often called the conversion efficacy, to differentiate it from the conversion efficiency. The so-called high-efficiency lamps possess a high conversion efficacy, i.e. a high amount of lumens per watt. In order to get a better bottom-up approach for the service sector's energy demand model, it is recommended to understand the shares of the different lighting fixtures in the service sector.

Conclusions

Service sector useful end-use energy demand and SVA have been found to relate a high correlation. There are still opportunities of improvement by adding other variables to the equation, e.g. floor space or employees of the sector. Nevertheless, this model brings a good starting point in terms of reliability for more complex additions.

Modelling service sector energy end-use of each region gives better insight of structural change. The new model gives a more detailed overview of the demand behavior per region. This model can be used to get more input for explaining the reason why a certain region has a higher share of electricity, or any other fuel for that matter. Space heating and space cooling use differences can be explained through differences in the heating and cooling degree-days. Energy carrier shares can be often explained through the end-use structure or by regional energy prices and fuel and technological availability, but information about the latter is not always available.

This model shows that, as long as the service sector maintains its growth, its final energy demand will increase globally. When looking at specific end-uses, it is clear that space heating loses the lead in end-use share to space cooling and appliances. A major shift into the use of electricity is also evident. Although fuel prices play a role in the energy carrier mix, since the energy costs of the service sector do not represent a major part of the sector's cost, their importance is not significant. Therefore, in order to mitigate CO_2 emissions it is necessary to instate efficiency policies. In that way, space heating and space cooling requirements can be reduced significantly. Also, the required energy to cover appliances and lighting requirements would be substantially diminished.

2.7. Model comparison

In this paragraph the projected final energy demand and accompanying CO_2 emissions in the building sector are compared and analyzed of seven models. We start with comparing the total CO_2 emissions originating from the residential sector, identifying differences and agreements. The aim of this model comparison is to have a better understanding of the projected CO_2 emission pathway by clarifying uncertainties between the models, and understanding the underlying assumptions that lead to the model results. The focus of the analysis is on the residential sector.

As mentioned in the section 2.1 the modelling of energy end use functions has the advantage that regional differences with respect to climate conditions, as well as structural change in time can be modelled explicitly. AIM/CGE, IMAGE, REMIND and POLES have been working on the representation of functions during the ADVANCE project (see the previous paragraphs on model development), and GEM-E3 indicated that they would like to take a step in this direction as well. In this model comparison therefore for a few models that contain end use detail we compare energy use and fuel shares per function. With this the aim is to understand the effect of explicit representation of energy end uses on the buildings model projections and at the same time compare model results in more detail. The models IMAGE, GCAM, AIM/CGE and POLES include different energy functions in the residential sector. MESSAGE has an explicit representation of cooking in South Asia. IPETS V1.5 and IMAGE distinguish between urban and rural energy demand.

Scenario description

Two scenarios have been compared:

- Baseline scenario
- Carbon tax scenario

The baseline refers to a standard model run baseline scenario, where no attempts were made to harmonize assumption on drivers. In the carbon tax scenario a carbon tax was applied from 2020 onwards with a growth of 5% per year where 30 USD is reached in 2040. In the Figure 16 the model drivers GDP per capita and global population are shown.

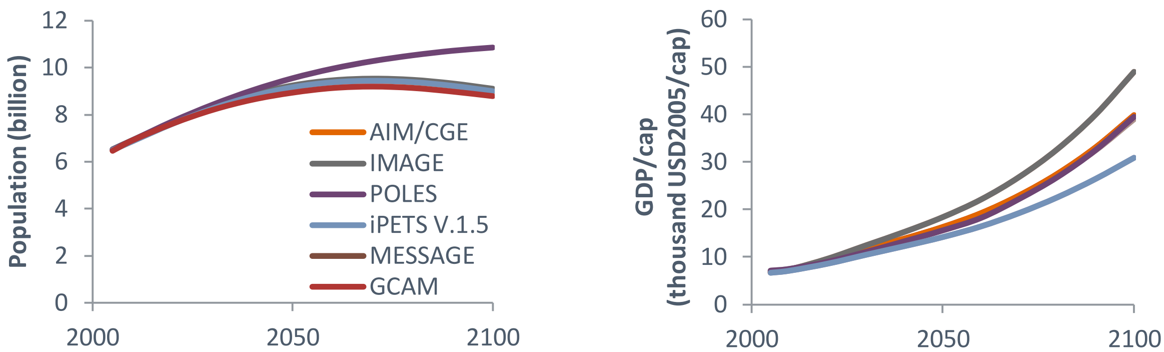


Figure 16 Scenario drivers: a) Global Population b) Global GDP MER per capita

In Figure 17 total residential CO_2 emissions are depicted of the two scenarios, differentiating between direct and total (incl. indirect) emissions. The direct emissions are projected to stay close to current values in the baseline by all models, and decrease slightly in GCAMs projections towards the end of the century. In the carbon tax scenario this effect can be seen in POLES and IPETS V1.5 projections as well. It is clear from the figure that the indirect emissions (originating from fuel combustion for electricity production) take up a large share currently, and this share is projected to increase further in the future in the baseline scenario. As CO_2 intensity factor decreases in all scenarios this implies an increase in residential electricity use at a global scale. In response to a carbon tax the indirect emission reduce significantly in all models. How fast this reduction occurs differs per model and has a strong correlation with the electricity CO_2 intensity as can be seen in Figure 18.

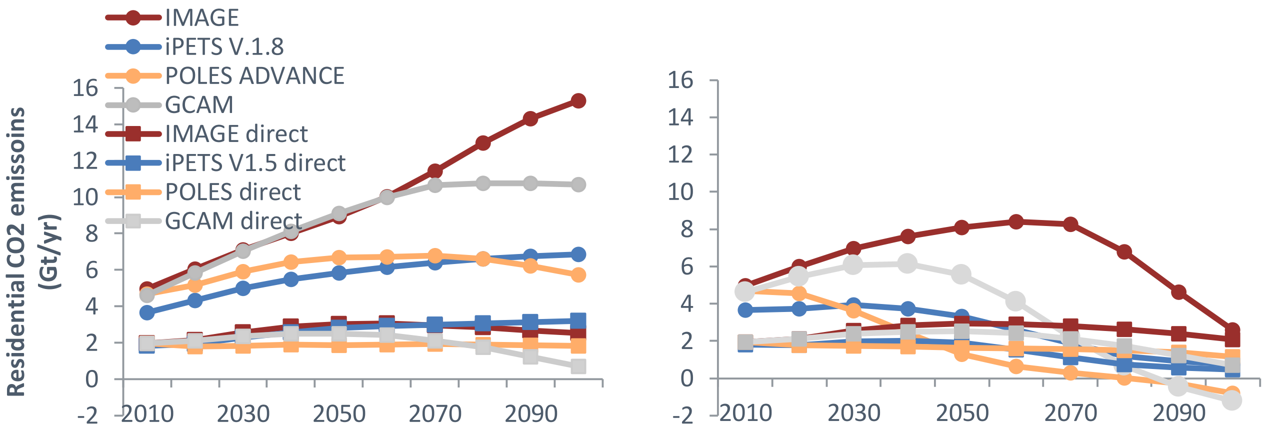


Figure 17 Total (incl indirect) and direct residential CO_2 emissions in a) baseline b) carbon tax scenario

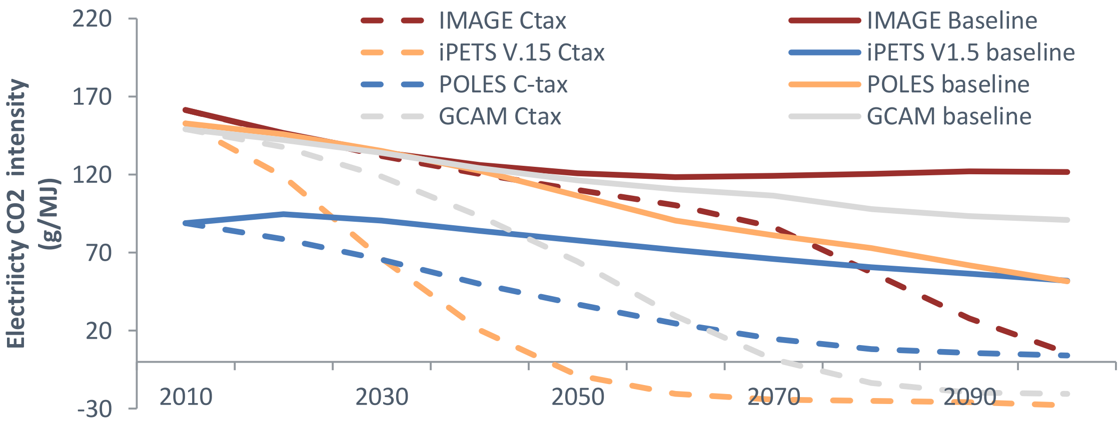


Figure 18 Electricity CO_2 intensity (CO_2 emissions associated with the production of electricity)

Final Energy

Most models project the residential final energy use to increase moderately in the coming century (Figure 19), considering that GDP drives residential energy demand in all models which is projected to continue to increase with at least a factor 5 in 2100 compared to 2010. This decoupling is illustrated in

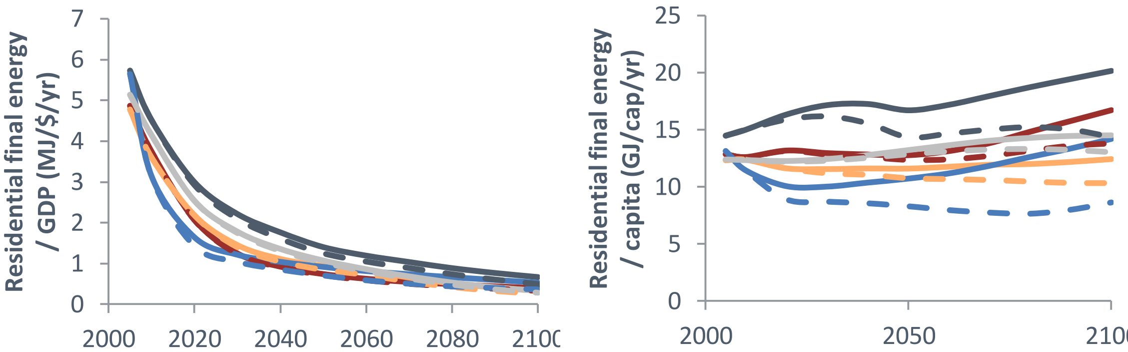


Figure 20. In response to the carbon tax the final energy reduces with 10% - 39% compared to the baseline scenario in 2100. However, there is not a clear baseline and mitigation energy use pathway: differences between the models are larger than between the scenarios.

Global residential final energy per capita is between 12-14 GJ/cap/yr in 2005 and is projected to increase slightly in the baseline scenario. In Asia consumption per capita increases with 3-8 EJ (from 8-9 t 11-17), while in OECD90 countries it decreases slightly (3 EJ) or remains the same to 2010 values (See A.3 Regional figures model comparison). Regional difference remain up to 2100 in the model projections. While the IPCC AR5 Ch.8 warns for doubling or tripling of buidlings energy use if current trends continue, including population growth, migration to cities, increased adequate housing for billions of people and lifestyle changes (Lucon et al., 2014), in the baseline scenarios compared in this study, this effect is not visible. This can be due to either combined effect of high increasing service demand along with strong efficiency measures in all regions, or the underlying assumption that service demand per capita does not change severely.

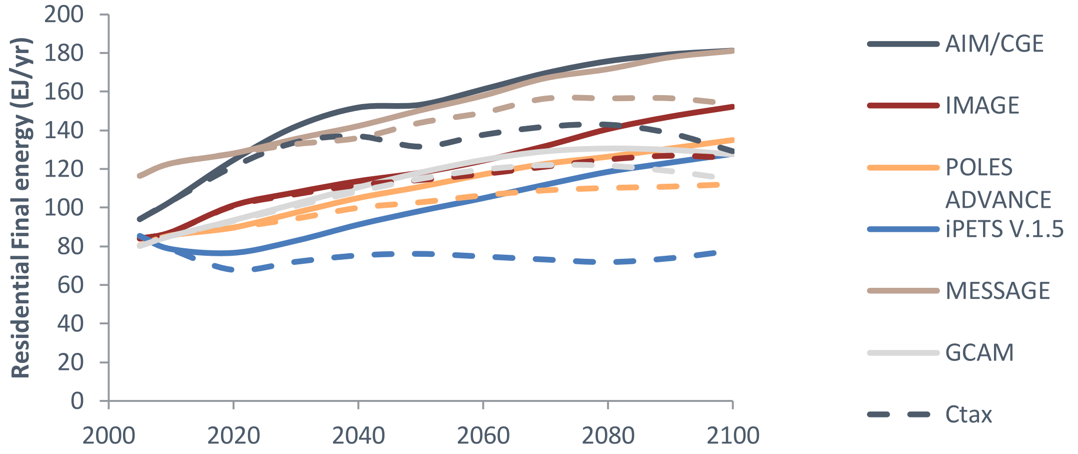


Figure 19 Residential Final energy in baseline (solid line) and carbon tax scenario (dotted line).

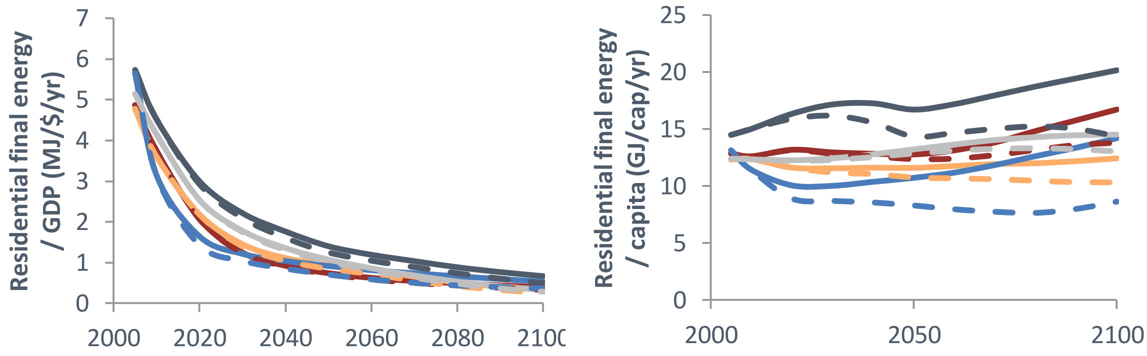


Figure 20 Global residential final energy per GDP (a) and per capita (b)

Energy Functions

This section takes a closer look at the demand for specific energy using functions, namely space heating, water heating, cooking, cooling, lighting, appliances and other (Figure 21).

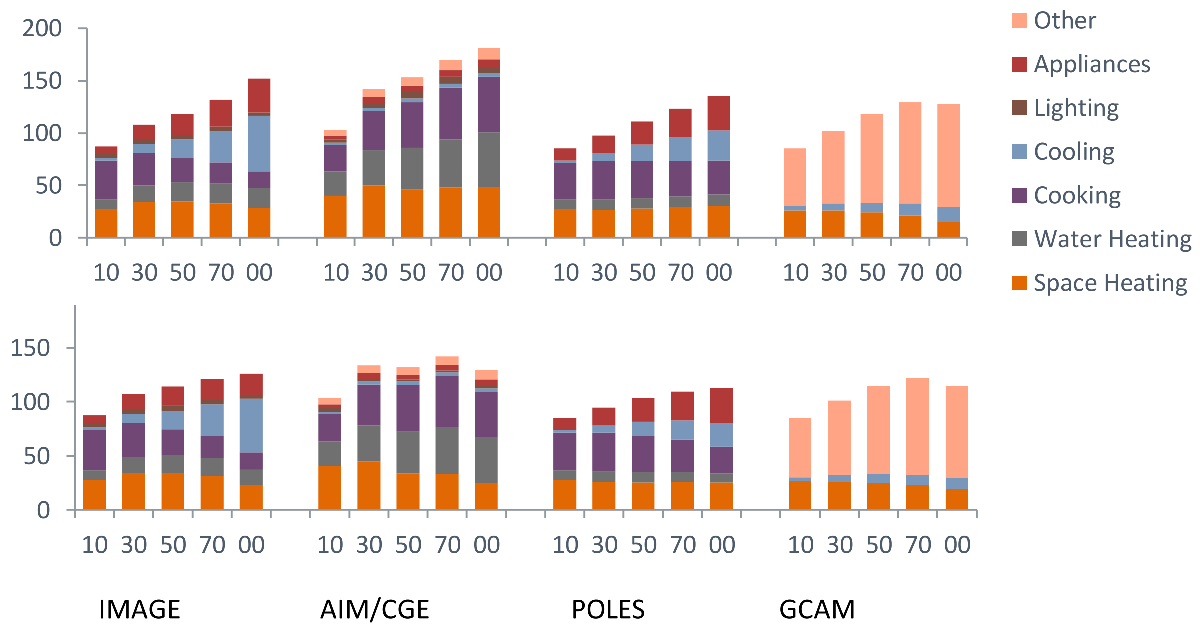


Figure 21 Global residential final energy per energy end use for the year 2010, 2030, 2050, 2070 and 2100. Top: Baseline scenario, Bottom: Carbon tax scenario.

IMAGE and POLES show a trend towards more appliances (and cooling in IMAGE) and less cooking in the future at a global scale. In AIM/CGE cooking and water heating shares increase slightly (both approx. 5%). In all models the demand for space heating decreases. Cooling and Space heating are dependent on climate conditions, differing per region. This variability can be seen in the regional figures in the appendix, where in OECD90 countries the demand for heating is more than 50% in all models. In IMAGE ASIA the shift from cooking as largest energy function to cooling is more pronounciated than at the global level. This effect is also visible in POLES but not visible in AIM/CGE projections. In all models the end use share hardly respond to the carbon tax.

The energy efficiency expressed in final energy demand per service demand for water heating and space heating are compared in Figure 21. In 2005 these values are different between the two models, due to mainly differences in assumed service demand. In AIM/CGE the values reduce lower than 1, since efficiency measures are applied at the final energy demand while service demand is not corrected accordingly.

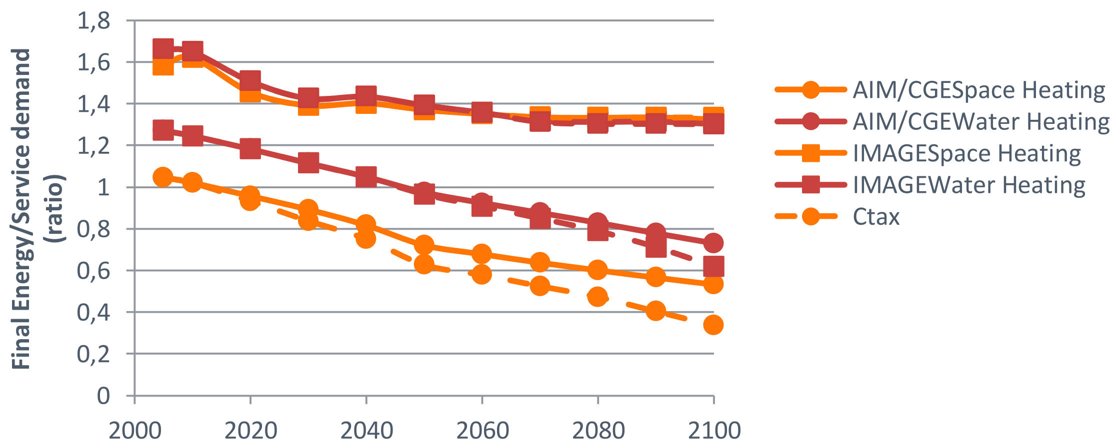


Figure 22 Efficiency development in baseline and carbon tax (dotted line) scenario expressed in final energy per service demand.

Lighting, cooling and appliances are likely to be powered by electricity, and the large shift toward cooling and appliances in IMAGE (>50%) and POLES (>30%) result in an increasing demand for electricity in the baseline (Figure 23). In AIM/CGE this effect does not occur, but electricity shares do increase in response to the carbon tax. MESSAGE and iPETS also show increasing electricity shares, which go slightly beyond the electricity fuel shares of those models that represent functions. Increasing demand for electricity explains the rapid increase of indirect emissions in the baseline scenario as seen at the start of this chapter.

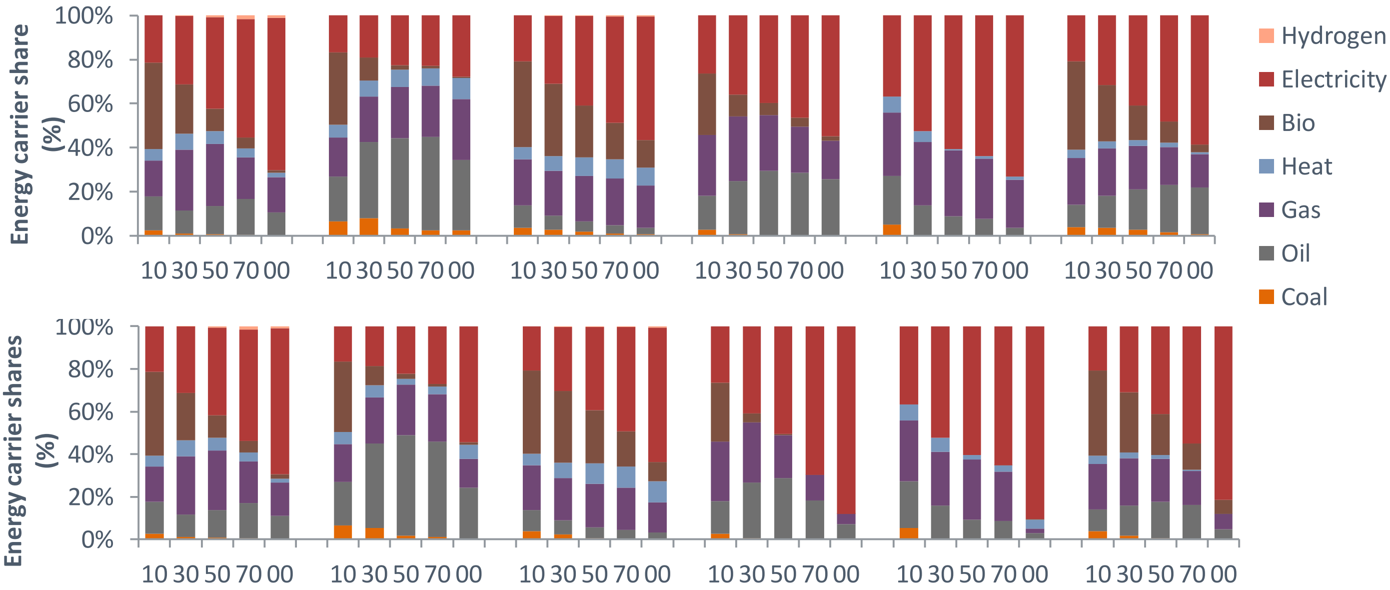


Figure 23 Global residential final energy per energy end use for the year 2010, 2030, 2050,2070 and 2100. Top: Baseline scenario, Bottom: Carbon tax scenario. F.l.t.r. IMAGE, AIM/CGE, POLES, iPETs, MESSAGE and GCAM.

Urban Rural

In the last section of this comparison, the urban and rural differences are compared between iPETS V1.5 and IMAGE. Differentiating between urban and rural has the advantage to distinguish between fuel preferences of the two groups. In rural areas currently there is a higher preference for biofuels, while in urban areas more gas and electricity is used. In addition projections for population growth in both areas, and thus extrapolating the current trend of urbanization, can be added to the scenarios. Both IMAGE and iPETS V 1.5 show a more rapid increase final energy growth in urban areas (probably due to this urbanization) and reduction of traditional biofuels use in rural areas. However modelling these trends explicitly has not lead to different energy carrier mixes in these models compared to the other models compared in this study, which also show reduction of biomass use at similar rates.

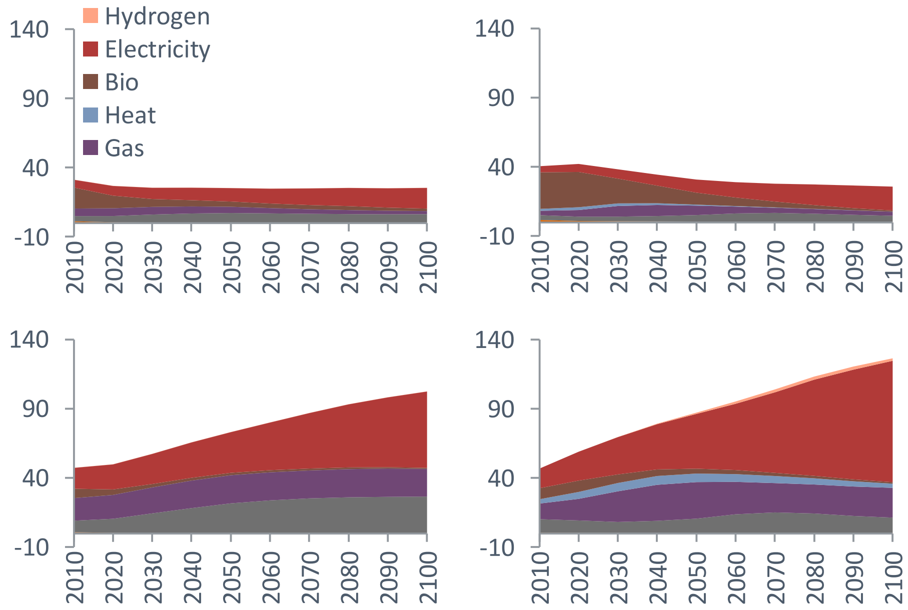


Figure 24 Global residential final energy in rural areas (top), and urban areas (bottom). The left column are model projects of iPETS and right of IMAGE.

Conclusions

- Final energy demand decouples from GDP growth in all models and is projected to grow between (50-93%) in baseline and (-9-50%) in carbon tax scenario compared to 2005 values. Clear final energy use scenario pathways cannot be distinguished and the differences between models are larger than between the scenarios.
- Regional variation in energy use/cap/yr continue to be present in the models throughout the century, and stay close to current values.
- All models show a shift towards electricity in baseline and carbon tax scenario, and the decrease in total emission (incl. indirect) is highly dependent on the CO_2 intensity factor of electricity production.
- Explicit representation of functions for these set of models seem to create a barrier shift towards electricity, or in other words results in different modelling behavior which differs from the top down models in this study. This effect is however moderate, and in a scenario achieving a 450 ppm (which has not been discussed in this study) all models sshift to >65% electricity in 2100.
- Modelling energy functions allows explicit representation of functional change (e.g. more cooling and appliances) in the future, distinguishing between regions, and representing energy efficiency potential per function. Between the models there is uncertainty in how these pathways will develop and how it effects fuel shifting, efficiency and end use demand. An improved understanding of these developments would be an important next step in model development.

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Appendix

A.1 End Use Functions REMG model

The demand of the five end use functions are determined in terms of *Useful Energy* (UE), that is, energy delivered to the end-use functions adjusted for conversion efficiency between energy carriers. The choice of functions and their relationship with the primary drivers is based on the methodology adopted by van Ruijven *et al.* (van Ruijven et al., 2011).In all the following equations the subscript '*R'* denotes regional variation*, 'p'* denotes urban/rural class difference, '*q'* denotes income quintile, and '*a'* different appliances. Below, we briefly discuss the relationships derived for each end-use function. A detailed account of the data analysis can be found elsewhere (Daioglou, 2010).

***Cooking**:* In developing regions, cooking often represents the most significant end-use function. In developed countries, however, other end use functions take precedence (IEA, 2006; Schipper et al., 1996). We analyzed historical data for cooking energy use from different parts of the world. The total range (69 data points) was 0.77 – 7.22 MJ_{UE}/cap/day. The vast majority of data points (44) clustered around 1.5 and 3.5 MJ_{UE}/cap/day. No statistically significant relationship was found between energy for cooking and income or geographical region. Therefore it was assumed that all regions have an average constant consumption of 3 MJ_{UE}/cap/day.

***Appliances**:* Appliances represent an important end-use function which can be directly related to household expenditures. Three different categories of appliances are modelled. These include 1) food storage and processing, 2) washing/cleaning and 3) entertainment. Within these categories eight indicative appliances are modeled. The appliance *penetration* is based on a gompertz function, equation (1). The gompertz function has been selected since its asymmetric logistic growth can model the uptake of appliances of poor households with a rapid initial growth followed by a gradual approach towards saturation.

$$Penetration_{R,p,q} = Saturation_R \times EXP\left(-\varphi 1_{R,p} \times EXP\left(-\left(\frac{\varphi 2_{R,p}}{1000}\right) \times HHExp_{R,p,q}\right)\right) \quad (1)$$

Here, *HHExp* is the household expenditures disaggregated for regions, urban/rural class and income quintiles. The *saturation* level is the maximum number of appliances per household, which may vary with time. The gompertz parameters (ϕ1 and ϕ2) are region and class specific determined via regressions on available data points (global if local data was not available) (Daioglou, 2010).

In order to determine energy use, the ownership levels are multiplied by the unit energy consumption. It is assumed that efficiency changes over time based on autonomous as well as a price induced energy efficiency improvements. The autonomous energy efficiency improvement describe in equation (2) is assumed to be a simple decay over time as verified from data (Bogdan & Bertoldi, 2008; Cardoso, MNogueira, & Haddad, 2010; CEC, 2009; IEA, 2004; Weiss, Junginger, & Patel, 2008).

$$UEC = \alpha_{R,a} \times \beta_{R,a}^{(-1971)} + UECm_{R,a} \quad (2)$$

Here α and β determine the rate of autonomous decline and *UECm* is an assumed lower limit to UEC (based on extrapolation of trends and available information on minimum energy consumption by end-use type) (Daioglou, 2010).

For the price induced energy efficiency improvement, the UEC is related to the cost of electricity (coe) as shown in equation (3). The parameter *coe* not only includes the electricity price, but also the annualized capital cost for use of electricity based on the current prices and efficiency ratings of certain appliances (Amana, 2010; Dixons, 2010; Whirlpool, 2010). The assumption is that appliance choice for each household is based on annualized total costs, weighing the advantage of reduced energy costs against the additional investments into efficiency. This price-induced efficiency improvement is assumed to occur on top of the autonomous improvement mentioned above. The coefficients α and β for equation (3) are determined based on the most attractive option for any given consumer discount rate (Daioglou, 2010). Thus for low-income households with high consumer discount rates where capital costs are important, the effect of a higher cost of electricity is lower. The consumer discount rate is discussed in greater detail in section **Error! Reference source not found.**.

$$UEC_{R,p,q,a} = \alpha_{R,p,q,a} \times Ln(coe_R) + \beta_{R,p,q,a} \quad (3)$$

Space Heating and Cooling: In richer households, space heating and cooling represents the greatest share of energy demand. Space heating demand is modeled as a function of floorspace (m^2/cap), population size (capita), heating degree days (HDD) and heating intensity ($kJ_{UE}/m^2/HDD$) directly after Isaac and van Vuuren (Isaac & van Vuuren, 2009).

$$HeatUE_{R,p,q} = Population_{R,p,q} \times FloorSpace_{R,p,q} \times UEInt_R \times HDD_R \quad (4)$$

In equation (4), *UEInt* is the useful energy heating intensity ($kJ_{UE}/m^2/°C/yr$) which is also sensitive to energy costs, with heating intensity reducing as costs go up based on available technologies. *Floorspace* is in m^2/cap and it is assumed to be a function of income levels and population density. The heating degree days are determined on the basis of a relationship with monthly mean temperature .

Energy use of air conditioners is based on their penetration, unit energy consumption (*UEC*) and efficiency improvement **(**5):

$$ACEnergy_{R,p,q} = Penetration_{R,p,q} \times \frac{UEC_{R,p,q}}{Efficiency\,Change} \quad (5)$$

The UEC is adjusted for efficiency changes to the average Energy Efficiency Ratio (EER) projections (Rong, Clarke, & Smith, 2007). The penetration depends on an expenditure based gompertz growth towards a climate based maximum saturation value. The relationship between maximum saturation and cooling degree days (*CDD*) is exponential and has a maximum of 100% (McNeil & Letschert, 2007; Sailor & Pavlova, 2003). The UEC has a linear relationship with the cooling degree days (CDD) and a logarithmic relationship with income in order to account for multiple ownership of air cooling appliances (6):

$$UEC_{R,p,q} = CDD_R \times (0.6053 \times \ln(HHExp_{R,p,q}) - 3.1897) \quad (6)$$

Again, CDD is based on a relationship with monthly mean temperature.

Water Heating: The growth in demand for warm tap water is modeled as a function of income towards a maximum value that is determined by heating degree days (cold regions tend to use warmer tap water). The data used to construct this relationship comes from a number of sources covering many climatic regions (DoECC, 2009; EIA, 2005; FSO, 2010; IEA, 2004; NRCan; Rosas-Flores & Galvez, 2010; Tyler & Schipper, 1990; Utlu & Hepbasli, 2005).

$$WaterUE_{R,p,q} = MaxUE_R \times \left(1 - EXP\left(3.356 \times EXP\left(-\left(\frac{0.237}{1000}\right) \times HHExp_{R,p,q}\right)\right)\right) \quad (7)$$

Where *MaxUE* in equation (7) is the maximum useful energy requirement for water heating based on a linear increase with HDD.

***Lighting**:* In low income countries lighting can account for a significant share of total electricity use while in OECD countries it represents only a small fraction of total energy use (IEA, 2008; Weiss et al., 2008). In households which lack access to electricity, lighting demand is met by a given quantity of kerosene (Mills, 2005). For electrified households, data suggests that lighting demand (at frozen efficiency) forms a linear relationship with floor space. Hence, we used the floorspace trends to estimate the number of lighting fixtures per household. This is multiplied by the average wattage of lights (assumed uniform), and provides the total lighting capacity of the household. Finally this can be multiplied by a Lighting-Hours factor (the equivalent time that all lights are on). The formula has been fit to the available data (Daioglou, 2010).

$$LightingEnergy_{R,p,q} = 0.68 \times Floorspace_{R,p,q} \times Wattage \times LightingHoursFactor \quad (8)$$

The wattage is determined by a choice between standard (incandescent) bulbs and efficient (compact fluorescent) lighting, based on the annual fuel and annualized capital costs. Market shares of the respective technologies are allocated based on the multinomial logit function (explained below). The costs of incandescent lamps are set as constant while there is a decrease over time in the price for compact fluorescent bulbs towards a minimum (Oosterhuis, 2007; Weiss et al., 2008).

A.2 Parameterization Gompertz function Service sector model

Gompertz	a	b	c	R^2
Appliances	12.36	4.073	0.057	0.904
Cooking	0.484	4.352	0.101	0.738
Lighting	7.401	3.626	0.051	0.901
Space Cooling	7.487	4.683	0.079	0.906
Space Heating	4	2.206	0.079	0.817
Water Heating	0.755	2.119	0.129	0.738

Gompertz function parameters used for each end-use equation, and their respective R squared from the regression analysis.

GLF	a	b	c	V	R^2
Appliances	6.1	591.95	0.117	196.292	0.923
Cooking	0.452	0.883	0.401	0.322	0.738
Lighting	7.381	-4.599	18.683	0.003	0.901
Space Cooling	5.022	17	0.135	5.102	0.920
Space Heating	4	10.017	0.065	5.538	0.839
Water Heating	0.749	-0.696	0.709	0.199	0.738

General logistic function parameters used for each end-use equation and their respective R squared from the regression analysis.

Hybrid	a	c	v	R^2
Appliances	10.674	0.403	0.181	0.904
Cooking	0.466	0.679	0.172	0.738
Lighting	6.31	0.33	0.204	0.901
Space Cooling	6.967	0.598	0.158	0.906
Space Heating	4	0.277	0.329	0.821
Water Heating	0.745	0.428	0.349	0.738

Hybrid function parameters used for each end-use equation, and their respective R squared from the regression analysis.

A.3 Regional figures model comparison

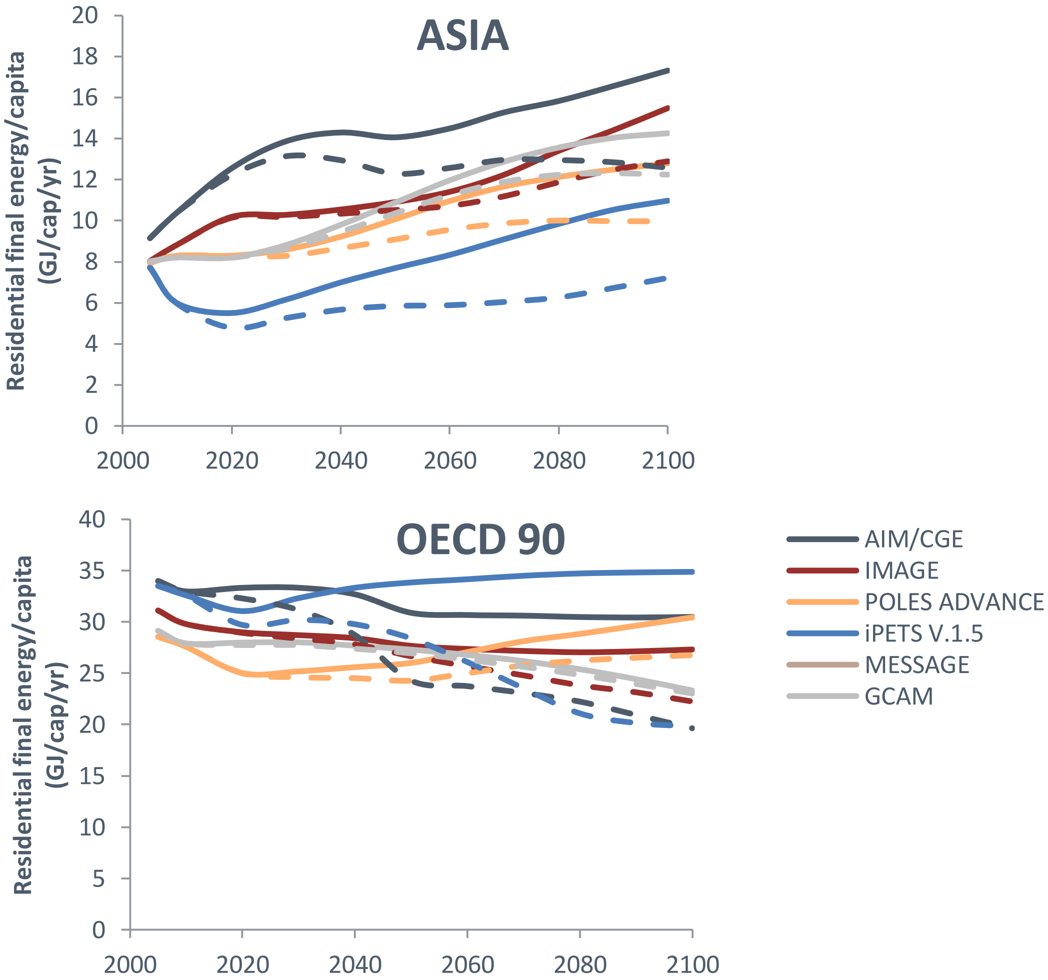
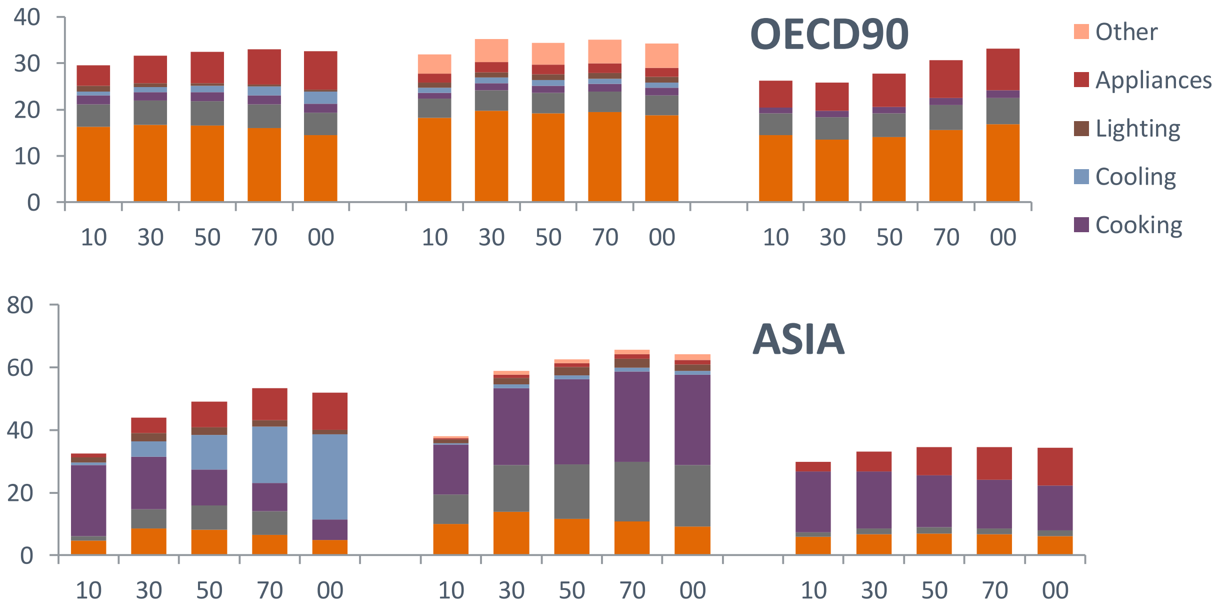


Figure 25 Global residential final energy per capita. Dotted line is carbon tax scenario.

Figure 26 Global residential final energy per energy end use for the year 2010, 2030, 2050, 2070 and 2100. Top: Baseline scenario, Bottom: Carbon tax scenario. F.l.t.r. IMAGE, AIM/CGE and POLES



3. Industry

3.1. Introduction

In this chapter first the results of a comparison study performed within the ADVANCE project will be presented, describing the IAMs model structure, model assumptions, and comparing industrial and cement sector scenario results. Secondly an description of the cement and iron and steel sector is provided, diving in the detail of the production process and important characteristics of the sector that affect energy demand and GHG emissions. Based on these modelling challenges in the Appendix the a guideline can be found for IAMs to enhance the representation of cement sector projection in the model. The modelling guide has been used to improve the demand and energy efficiency projections in the IMAGE model, presented in section 4.

3.2. Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models.[1]

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In 2010 37% of global final energy was consumed by industrial activities. Moreover, between 2005 and 2010 annual industrial greenhouse gas (GHG) emissions increased from 10.4 $GtCO_2eq$ to 15.4 $GtCO_2eq$, emitting more than any other end-use sector (IEA 2012; IEA 2013; M. Fischedick 2014). While the adoption of energy efficiency measures and the improvements in material efficiency have in the past decades reduced industrial energy intensity globally, the increasing demand for industrial products has still resulted in an increase in global industrial energy use. The International Energy Agency (IEA 2012) projects that if current trends continue, in the next 50 years the industrial energy use could more than double from 126 EJ[2] in 2009 to 250-270 EJ in 2050. For the same period, accompanying GHG emissions are projected to increase by 45-56%. It is clear that to reach stringent climate targets, effective climate change policies will need to be adopted in the industry sector (M. Fischedick 2014).

Integrated Assessment Models (IAMs), have been frequently used to identify strategies for different climate targets. Based on the previous paragraph, it is clear that a good representation of future emissions and mitigation potential of the industry sector is needed in these models. However, a complicating factor in representing energy demand in IAMs in general is that energy end-use sectors are highly diverse, and many different energy functions and technologies play a role. This is also particularly true for the industrial sector, where energy is used in a variety of ways to produce many different materials[3]. These materials can be divided into the subsectors iron & steel, non-metallic minerals, chemicals & petrochemicals, pulp & paper, non-ferrous metals and other products. For the manufacture of each of these industrial products, very different production processes are used, with a range of fuel types and energy intensities. Moreover, over time the production process characteristics change as a result of changes in the demand for industrial goods, technological changes, and sectoral changes, but also due to the increasing trade of industrial products, and of outsourcing production components (Liu and Ang 2007; OECD 2011).

[1] The model comparison study has been submitted to the peer reviewed journal Energy.
[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.
[3] In this paper the term industry is used for all activities contributing to the production of goods and construction of building and infrastructure.

Over the last few years, several model comparison studies have been published looking at the behaviour of integrated assessment models. Such studies have focussed on the energy and land-use systems as a whole, and on specific sectors and technologies (such as transport and bio-energy (Girod, van Vuuren et al. 2013)). A similar comparison, however, has not been performed for the industry sector. There are different types of IAMs with varying degrees of complexity and purpose. While the industrial sector is represented in most IAMs in an aggregate manner, some models include more detailed industrial sub-sectors. In this study, we address how these structural differences translate to model outcomes with respect to the future evolution of energy intensity, and the response of the industrial sector to climate change mitigation policy. We focus our attention on IAMs and energy-system models, which from here on will be called long-term energy models.

This is done by 1) comparing the structure and major assumptions of the models on the basis of a survey across the models, 2) performing a comparison of scenario results for a baseline and mitigation scenario, and 3) looking into detail into one major industrial subsector in terms of global energy consumption and emission generation - the cement industry - to assess the more detailed sector representation of some models. Through these means we aim to have a better understanding of 1) the projected mitigation potential of the industrial sector, 2) the means through which emission reductions are achieved in the models, and 3) the uncertainties in projections by identifying model differences.

The article is structured as follows. First in Section 2, we briefly present the various representations of the industry sector in models. In Section 3, model output for two scenarios are discussed, i.e. i) a "baseline scenario" where current trends continue and significant improvements beyond business-as-usual in energy intensity are not considered and ii) a mitigation scenario, where CO_2 emissions are mitigated and concentration levels stay below 450 ppm ("450 ppm scenario"). In Section 4, specific attention is given to the modelling of the cement industry. Finally, Sections 5 presents the discussion and conclusions paragraphs.

3.2.1. Method

Model structure and assumption comparison

The models included in the study can be classified as Integrated Assessment Models, indicating that they describe the interaction between the human system and the natural environment, i.e. climate change, energy use and land-use, or energy system models that focus on the energy system. The description of the industry sector varies significantly across the models with a varying degree of complexity and purposes. In order to better understand the representation of this sector, a descriptive questionnaire has been filled in by eight models participating in this study to compare the model structure, main assumptions and system boundaries in presenting the industry sector.

Scenario description

To compare the different models, key industrial model outputs of *two scenarios* were collected based on an earlier study for the Energy Modeling Forum (Kriegler, Weyant et al. 2014) and specifically for the EU- FP7 ADVANCE project:

- one scenario without new climate policies (baseline) and,
- one scenario aiming at a stabilization level at 450 ppm CO_2-eq (mitigation).

With respect to the baseline scenarios, models were asked to provide a medium-growth baseline but no attempt was made to harmonize assumptions – thus taking different demographic and economy growth rates as part of the overall uncertainty (see Section 3.2). The baseline scenario is compared to the *current policy scenario* of the WEO, which takes into account those policies and measures which affect energy markets that were formally enacted as of mid-2013, while the mitigation scenario is compared to the WEO *450 scenario*, which also stabilizes at around 450 ppm CO_2-eq in 2100 (IEA 2013).

Projections of socio-economic drivers

The model drivers, global population and GDP, expressed in market exchange rates and purchasing power terms, are depicted in Figure 1. For reference, we also show IEA's World Energy Outlook (WEO) scenario. In the WEO scenario world GDP (expressed in real purchasing power parity [PPP] terms) is projected to continue to grow between 2011 and 2035 at an average annual rate of 3.6%, doubling in size in this period. Population, a fundamental driver of energy demand, grows from 7.0 billion in 2011 to 8.5 billion in 2035 (IEA 2013). Most models scenario drivers stay relatively close to these assumptions in the coming decades, and start to diverge after 2035.

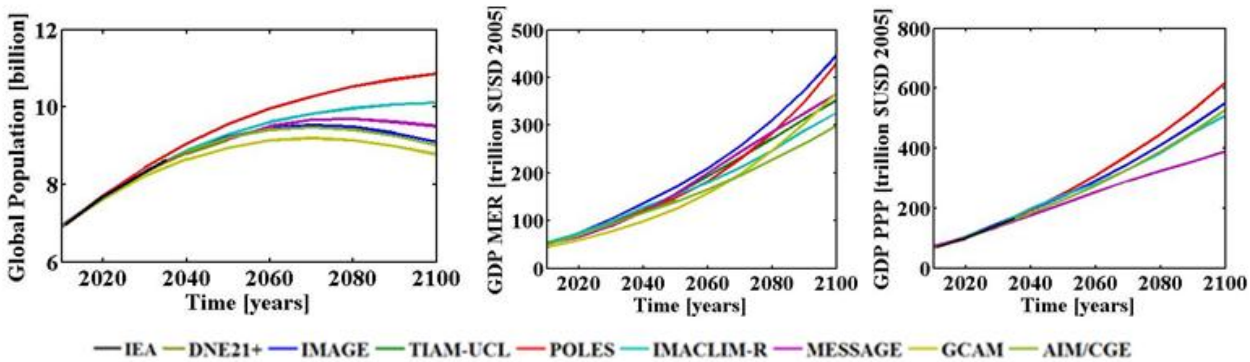


Figure 1: Scenario drivers: a) Global Population; b) GDP expressed in Market Exchange Rates; c) GDP expressed in real purchasing power terms.

3.2.2. Stocktaking – Industry sector in global energy system and IAM models

Overview of the IAM Industry sector representation

The models looked at in this study are: AIM-CGE, DNE 21+, GCAM, Imaclim-R, IMAGE, MESSAGE, POLES and TIAM-UCL. The models are briefly introduced in Table 1 in terms of their general characteristics.

Table 1: General characteristics of the models studied.

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

There are a few key differences between the models. 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. Given the heterogeneity of energy demand sectors, however, the amount of detail in demand-side representation in the models is often far more limited than the supply side. Most of the 'bottom-up' models are energy-system models representing the behavior of the energy system. Top-down models contain 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 Computable Generic Equilibrium (CGE) models, representing the sectoral economic activities by production functions (Löschel 2002). Another key difference across the models is the solution type. Many models are optimization models, i.e. an algorithm is used to optimize a distinct target (depending on model type mostly maximizing consumption or minimize energy system costs) across a period of time. Other models are simulation models, i.e. a set of rules determines the decisions made in every single time-period based on the information from the previous time step. The diverse set of models included in this study give a good representation of the broad range of type of long-term energy models.

3.2.3. Industry sector representation

All models include the industry sector as a whole, and some models split the sector up in different subsectors, with varying choice of which subsectors are modelled. Table 2 shows the model details with respect to the industry sector representation as well as the different subsectors covered by the models.

While some models relate industrial energy demand directly to economic drivers, based on historical relations observed, other models first derive the demand for materials. Modelling material demand gives the opportunity to include an explicit representation of the competition between various material production technologies and material recycling, thereby impacting industrial energy use (Allwood 2011; M. Fischedick 2014). When the activity is the outcome of a production function, energy efficiency is typically represented by the substitution between capital, material, labor and energy inputs.

Table 2 also indicates that some models include various industry-specific technologies that are selected on the basis of relative costs, leading to more efficient technologies deployed when fuel prices increase, while others do not model technologies explicitly. The representation of technology improvement differs from exogenous assumptions to learning-by-doing based functions.

An important issue is the assumption on system boundaries. Key differences among models are the inclusion or not of the energy use for feedstock purposes (also known as non-energy use of fuels), the energy use in coke ovens and blast furnaces in the iron and steel industry. Energy use in refineries, and non manufacturing industries agriculture and forestry are not included in the models industry data reported.

The main differences between the models assessed in this study can be found in the breakdown of industrial subsectors, explicit representation of material demand, drivers used to project final energy demand, explicit modelling of technologies and energy efficiency change. 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 Appendix.

Table 2. Main industry model characteristics. Information acquired primarily from the FP7 EU ADVANCE industry models stock taking.

IAM	Industry sector drivers	Industrial subsector breakdown	Technology	Efficiency improvements	Policy measures	Policy impact	Material trade (industrial goods)	Stock turnover	Recycling	Energy use as feedstock	Energy in coke oven and blast furnaces [3]	Process emissions [4]
AIM-CGE	CES production function with the energy nested with value-added	Iron and steel[2], chemicals[2], non-metallic minerals[2], food processing, pulp and paper[2], 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[1], cement[1], pulp and paper[1], aluminium, some chemicals[1] (ethylene, propylene and ammonia) (7)	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[1], nitrogenous fertilizers[1], 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	Endogenously from the equilibrium point between the supply and demand of industrial goods	None	No, only for CCS in cement and fertilizer	Autonomous, and fuel price induced energy efficiency	Carbon/energy taxes (or energy subsidies), emissions permits	Price mechanisms	Yes	Yes	Yes, but not explicitly	No	No	No
IMAGE	Material demand is related to economic activity and material intensity for steel and cement; energy	Steel[1], cement[1], other (3)	Steel, cement	Exogenous per technology more efficient technologies get a larger market share in response to	Carbon tax, prescribing certain efficient technologies	A dynamic response to changed technology costs (incl.	Yes, only for cement and steel	Yes	Yes	Yes	Yes	From cement

	intensity for other sectors			higher fuel prices.		fuel price) or prescribed technology mix						
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 CO2 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[4]	Price mechanisms and model constraints	No	No	No	Yes	In steel sector: yes, other sectors: no	From cement
POLES	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[1], chemicals and petrochemicals[2], non-metallic minerals[2], 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.	Price mechanism	Yes	(only for boilers)	No	Yes	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[1], chemicals[2], iron and steel[1], non-metallic minerals[1], 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	Price mechanisms and model constraints	Yes, but not explicitly modelled	Yes	No recycling	Yes	Yes	No

[1] Modelling physical production and energy demand of the subsector; [2] Modelling energy demand of the subsector ;[3] transformation and own energy use; [4] The process emission that can be assigned to a specific sub sector.

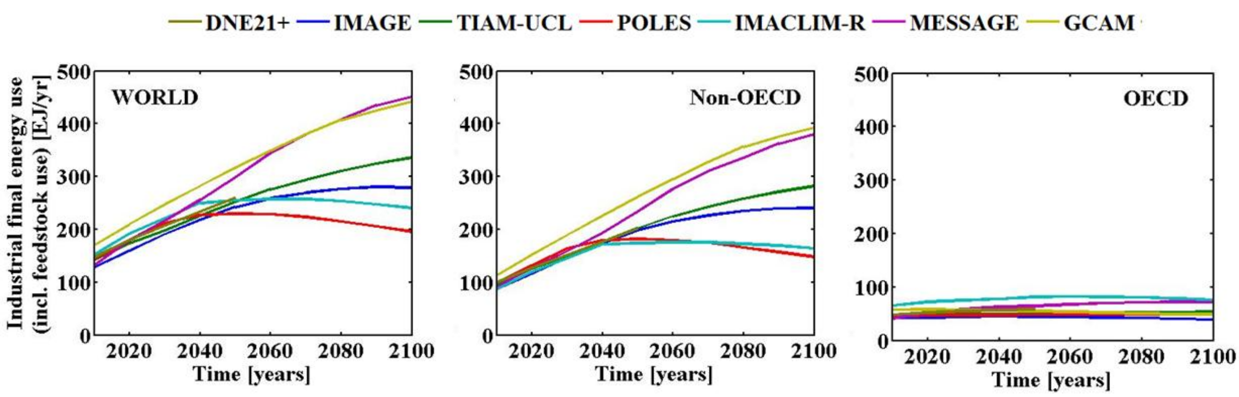
3.2.4. Global industrial model projections

3.2.4.1. Baseline projections

Final Energy Demand

Figure 2 shows the industrial final energy demand of each model (with and without feedstock use), compared to the WEO current policy scenario. In the short-term (next 20-30 years), all models project a steady increase of industrial final energy use, similar to the IEA projections. In the long-term, however there are clear differences in overall trends, though these differences are not clearly related to model structural differences. MESSAGE, TIAM-UCL, DNE21+ and GCAM project a continuous increasing energy demand, while the other models, such as POLES, Imaclim-R and IMAGE, show a saturation of energy demand over time. In 2100, this results in a range of more than a factor 2 between the highest and the lowest projection.

Figure 2: Baseline final energy demand projections for the industry up to 2100: a) global, b) Non-OECD countries and c) OECD countries.



Looking at the regional disaggregation, it can be seen that the final energy pathway of Non-OECD countries is key to understanding these global trends (Figure 2b,c). All models project annual industrial final energy use in OECD countries to remain more or less constant, while in Non-OECD countries industrial energy use is assumed to grow, however models differ in their assumption on how long this growth continues.

Energy intensity trends

All models show a decoupling of industrial energy demand and economic growth, continuing the historical trend of reducing energy intensity (see Figure 3). This can be the result of economic structural change (slower growth of industry sector activities than the overall economy), shifts towards higher-value goods produced by the industrial sector, and improved energy efficiency within an industrial sector. Historically, the reduction in energy intensity has been higher in developing countries than in developed countries, but starting from a much higher position. Literature suggests that a key factor in the energy intensity decline in developing countries has been technological change while in developed countries structural change has had a large impact recently (UNIDO 2011; Olivier 2013).

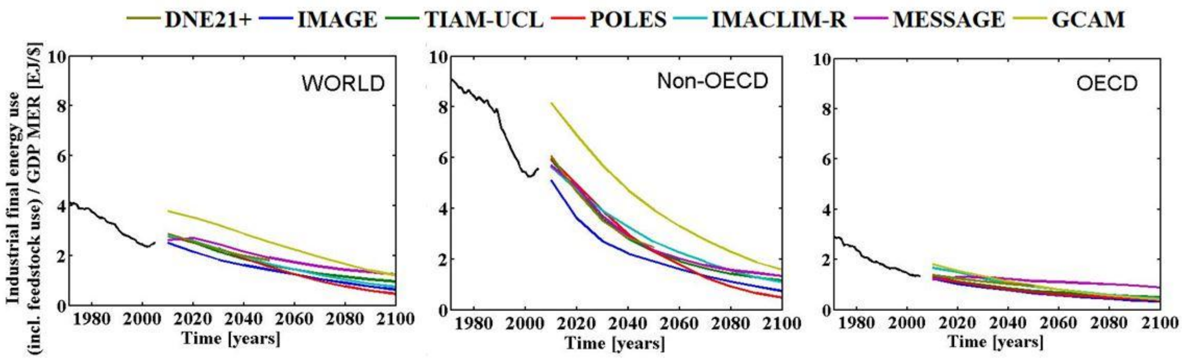


Figure 3: Industrial energy intensity expressed in final energy use/GDP MER (in USD $2005) for different regions: a) global, b) Non-OECD countries and c) OECD countries.

All models project the energy intensity of Non-OECD countries to continue to decrease at a similar rate as seen in the last decades, in the near future. However in the long run the model projections differ in how long this improvement continues. In OECD countries energy intensity decreases slowly but continuously in time reaching more than 60% reduction in 2100 in nearly all models compared to 2010 values. A key uncertainty for future industrial final demand is thus whether energy intensity in non-OECD countries converges to the level of the OECD countries.

Energy consumption by fuel type

In Figure 4 the projected industrial final energy per fuel type is shown for the year 2010, 2030, 2050 and 2100. The AIM/CGE and IEA results do not include industrial feedstock use. Interestingly, there is a reasonably large agreement across the models in the shares of different fuels over time. Fossil fuels are projected by all models to take up more than 50% of the industrial fuel use in 2100. Most models, except Imaclim-R and TIAM-UCL project a slight increase in electricity use and a decrease in fossil fuel use, both between 10-20% change.

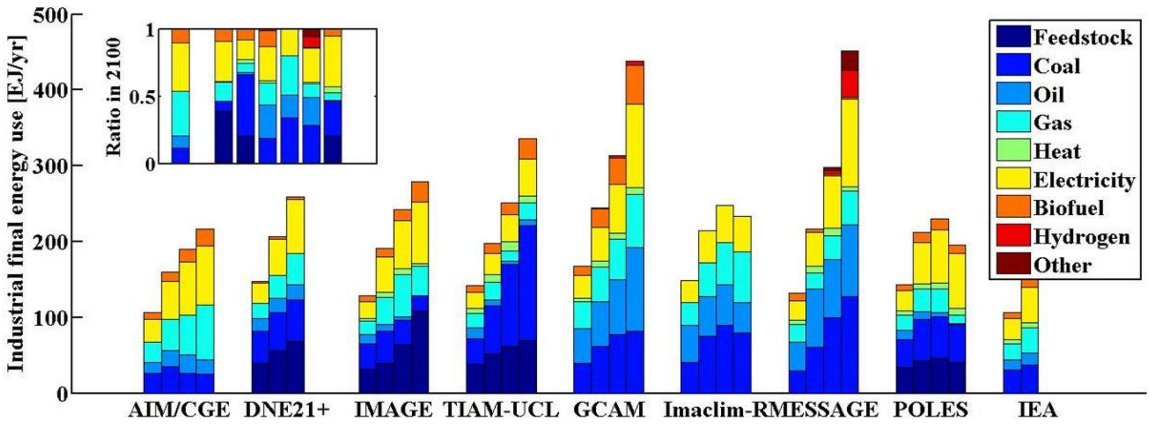
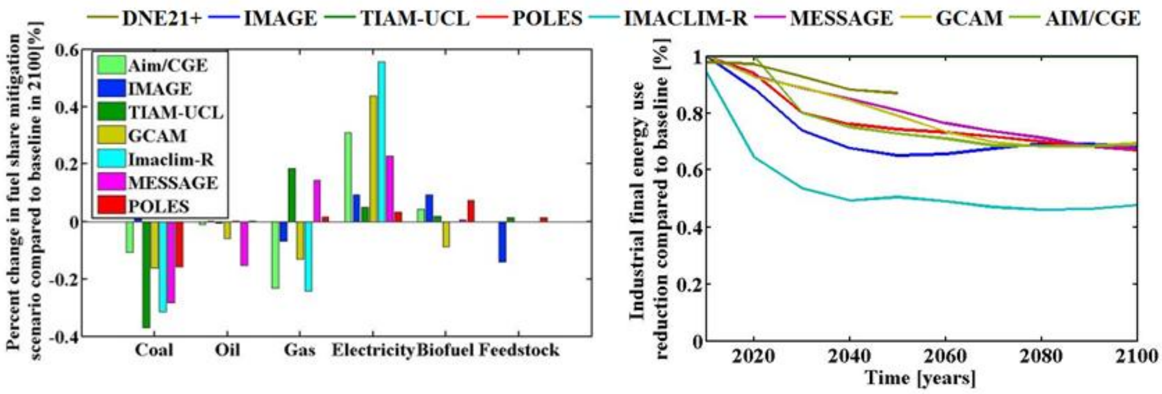


Figure 4: Baseline final energy demand of the industry per energy carrier in 2010, 2030, 2050 and 2100. The reported values include feedstock use for MESSAGE, GCAM and IMACLIM, which in 2010 is mainly oil use in the chemicals and petrochemicals sectors, and cokes in the iron and steel sector. In the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

3.2.4.2. Mitigation scenario projections

In the stringent climate policy scenario all models show a decrease in final energy demand compared to the baseline (Figure 5b). The range of industrial final energy use in 2100 drops from 195-451 EJ to 115-306 EJ, i.e. within each model, the reductions span a range of 10%-50%. The two main groups shown for the baseline projections are maintained: GCAM, TIAM-UCL, DNE21+ and MESSAGE show a growing final energy use, while Imaclim-R, IMAGE and POLES project saturation of final energy demand. In terms of the reduction to baseline, 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 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 than in the other models.

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



The fuel mix changes significantly in the mitigation scenario which can be seen in Figure 6a, showing the percentage change in fuels shares in 2100 between a mitigation scenario to 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 TIAM-UCL show a significantly lower use of fossil fuels in the mitigation scenario. The general trend is a decrease in coal use and an increase in the use of electricity to reduce industrial emissions. This transition takes place steadily over time. TIAM-UCL is the exception, with a relatively low share in electricity use in 2100, and switch from coal to gas.

Oil and biomass shares do not change severely in all models. The apparent shift towards electricity is significantly larger for AIM/CGE, GCAM, Imaclim-R and MESSAGE than other models. It should be noted though that these models do not model specific industrial manufacturing processes explicitly, which could explain a higher flexibility in fuel switching. In technology-rich models the additional information on preferred fuels for different processes and/or the lack of more advanced technologies in the model's representation could constrain fuel switching.

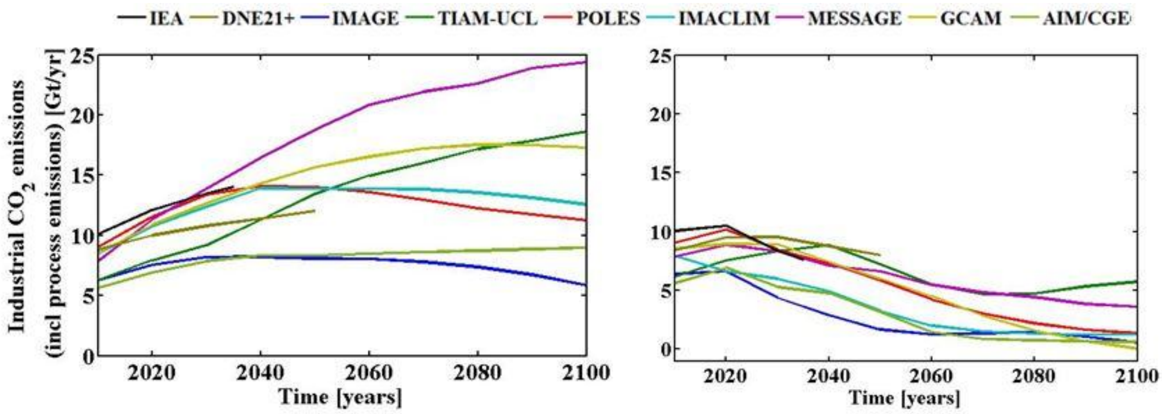
This divergent behavior highlights a broader issue that is relevant for modeling future industrial energy use: that is, the appropriate level of detail at which to model the products manufactured, and the specific of the manufacturing technologies used. In this exercise, the more aggregate models tend to represent many industrial subsectors together with generic production technologies in which all fuels are substitutes, which may be unrealistic for many specific processes. However, process-based, technologically detailed models may not have the capacity for future fuel-switching at levels that would be consistent with historical observations, simply because the technologies that would enable future fuel-switching do not currently exist. For example, electric arc furnaces in the steel industry and mechanical separation technologies in the chemicals industry have led to increasing shares of electricity in both of these industries in the past few decades.

CO_2 emissions

Figure 6 shows the CO_2 emissions from industrial energy consumption for the baseline scenario as well as the mitigation scenario, including process emissions. In the baseline MESSAGE, TIAM-UCL and

GCAMs CO_2 emissions continue to increase, given the increase in energy demand, combined with an increasing share of coal in MESSAGE and TIAM-UCL. In IMAGE, POLES, Imaclim-R and AIM-CGE emissions stabilize in the second half of the century. In the mitigation scenario all models sshow a reduction of CO_2eq emissions, with comparable reduction rates in time (Figure 6, right-hand side). Large differences in reduced industrial emissions and thus mitigation potential are apparent, resulting from the extent and rapidness of energy consumption reduction, and flexibility to switch fuels as discussed in the previous paragraphs.

Figure 6: Total CO2e emissions incl. process emissions in a) baseline scenario and b) mitigation scenario.



3.2.5. The cement industry – subsector model comparison

To get a better impression of how the industrial sub-sectors are represented in the models, in this section we have a closer look into the projected material production and energy use for the cement industry of the IMAGE, DNE21+, AIM/CGE, POLES, GCAM and TIAM-UCL models for the baseline scenario (only for these models data was available). For comparison, also the IEA projection for the 6°C scenario (6DS) is shown (IEA 2012).

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 $GtCO_2$ which is 26% of global industrial GHG emissions of which more than half were process emissions from calcination (IEA 2011). Several studies have identified technologies/measures that can limit the energy use and GHGs, and improve material efficiency in this sector (WBCSD/CSI-ECRA 2009; JRC/IPTS 2010; Worrell 2013). Another reason to focus on this sector is that, compared to the other major energy intensive industries, the cement industry is less complex. The commodity produced is homogeneous, and 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 (Harder 2008), meaning that for most countries, and certainly the large regions covered in models, cement production is equal to cement consumption.

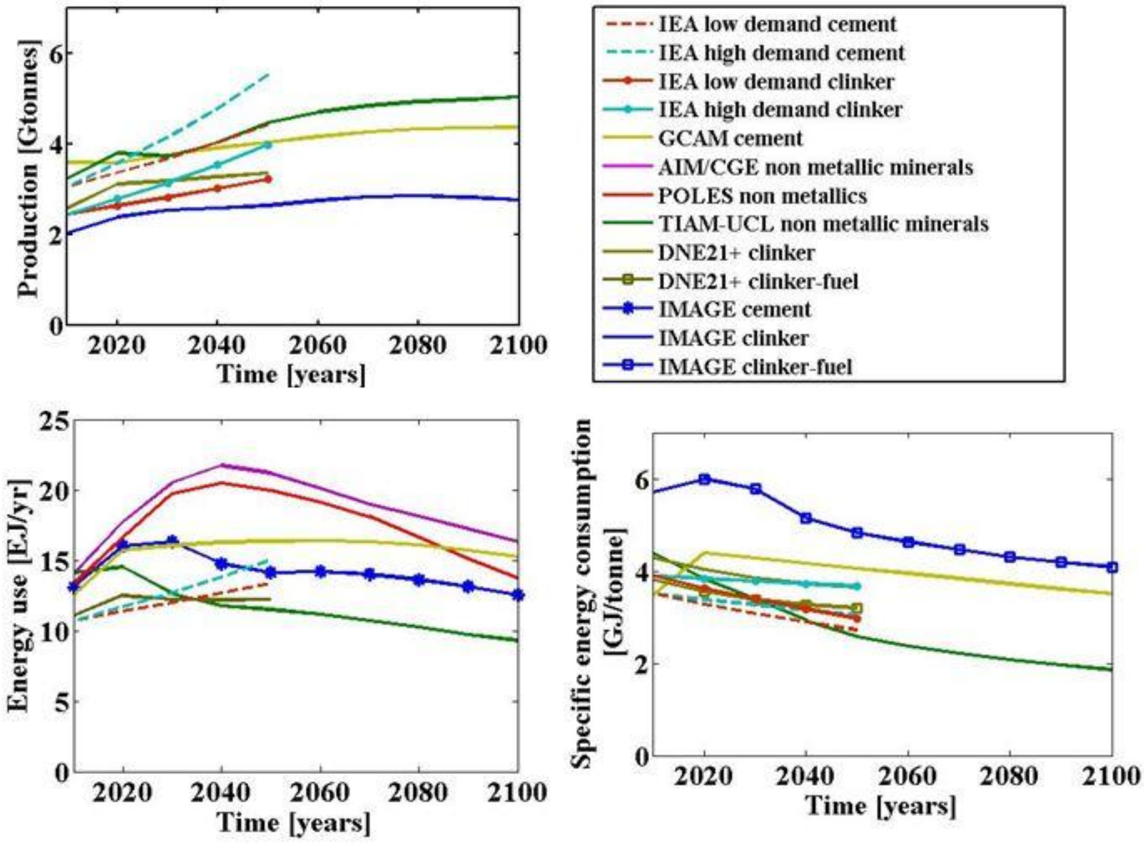


Figure 7: a) Projected material production in the non-metallics/cement industry b) energy use c) specific energy consumption for cement and clinker making in different long-term energy models under the baseline scenario in different long-term energy models in comparison with the IEA projections

Figure 7a shows the projected production of cement in three models (TIAM-UCL, DNE21+, and IMAGE), that model material use explicitly[4]. The global cement production in 2010 was 3.2 Gtonnes (USGS 2013) and the global estimated clinker production was 2.4 Gtonnes (based on a clinker to cement ratio of 76%)[5] (WBCSD/CSI 2012). In IEA, clinker production increases from 2.4 Gtonnes in 2009 to 3.2 and 4.0 Gtonnes in 2050 under the low demand and the high demand scenarios, respectively. Compared to the IEA projections, the three models forecasts are on the low side of the projections. This is due to lower growth rates and different calibration years (IMAGE is calibrated to 2005). In addition all long-term energy models show a saturation of demand, while the IEA projects steady growth.

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 (Figure 7b). 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 continues growth rates, in line with the earlier observation on material production rates. The models show again show difference in base year data. All models project that the cement sector share in total industrial final energy use decreases.

Figure 7c shows the development of specific energy consumption (GJ/tonne product) for cement and clinker making in the various energy models. This is projected to decline in all models driven by

[4] The DNE21+ and IMAGE models refer to clinker production, while the TIAM-UCL model to non-metallics production.

[5] 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.

technology development (with exception of the IMAGE 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 (IEA 2012). 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, compared to the IEA 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 (JRC/IPTS 2010) 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 (IEA 2012; Kermeli, Graus et al. 2014). This means that considerable improvement of the energy intensity would still be possible in the mitigation scenarios.[6]

The detailed focus on the cement sector here shows that understanding how total industrial projections relate to subsector material, energy demand and technology deployment improves the ability to interpret the scenario results.

3.2.6. Discussion and conclusion

3.2.6.1. Discussion

The industry data comparison has shown that the models project different energy intensity pathways and fuel switching opportunities to mitigate emissions. Sector-specific case studies and bottom-up details could improve projections, and increase the ability to assess sector specific mitigation policies. Using energy intensities of specific countries/regions, in combination with projected material demand to model industrial future energy, could help to understand the role of recycling, material efficiency, and technology efficiency in mitigating emissions. This can help to clarify 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, improving the material efficiency in cement making, by using higher amounts of supplementary cementitious materials at different stages of cement production, or by using higher amounts of recycled or crushed concrete in the production of new concrete.

In addition modelling material demand at sub sectorial level would give 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 construct future infrastructure and building requirements, which could give more guidance in better projections of material demand saturation.

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.

[6] The IMAGE energy intensity values are relatively high as they are the energy use for cement making divided by the tonnes of clinker production.

3.2.6.2. Main conclusions

This study presents the first comparison of the industrial sector in long-term energy models. The industry sector consumes 37% of the global final energy use and currently emits more GHG emissions than any other end use sector. Effective mitigation strategy to reach a climate target will also require a significant reduction of industrial emissions. Long-term energy models which are used to identify strategies to mitigate emissions, have been compared to understand by what means industrial emissions are reduced, and where uncertainties in model projections lie.

In the reference baseline scenario, the projected behavior across the models is comparable in the coming decades: the industry sector is relatively energy intensive and remains reliant on fossil fuel (>50%)– but in the second half of the century energy use models project either continuous growth or saturation. This leads to more than a factor 2 difference between the highest and the lowest industrial energy demand projection in 2100. 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 CO_2 emissions, where uncertainties are the potential of fuel switching or energy intensity improvements. The level at which industrial energy consumption can be decoupled from GDP growth varies across the models, showing alternative assumptions of the sensitivity of energy intensity to increasing energy prices. The reduction of final energy use in 2100 compared to the baseline scenario span a range of 10%-50%. The models show a switch from coal to electricity use as a measure to reduce industrial emissions. Explicitly modelling industrial technologies can constrain the flexibility to use different fuel types and this is recognized in the mitigation scenario results, as models with rich technology representation tend to project less variability in to switch fuels as a measure to mitigate GHG emissions. This divergence highlights that understanding of economy-wide mitigation responses and costs is an area for future improvement in the models.

Using industry subsector material and energy use details to support the projected mitigation potential can provide insight in feasibility of how emissions reduction can be achieved. More information at a subsector level could improve the understanding of what realistic energy intensity improvements as a result of material usage and technology efficiency changes are, 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 subsector specific climate policies to mitigate emissions.

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3.3. Enhancing the representation of energy demand developments in IAM models – A Modeling Guide for the Cement Industry[7]

Author: Katerina Kermeli, University of Utrecht

3.3.1. Introduction

Cement is an inorganic, non-metallic and finely ground grey powder which when mixed with water forms a paste that sets and hardens. Due to its binding properties, cement is used in combination with aggregates and water to form concrete. The typical cement content in concrete is in the range of 10 and 15% (PCA, 2013).

Concrete is a key building material widely used in the construction of buildings and civil engineering. The type of cement most widely used in concrete production is Portland cement (IPTS/EC, 2010). The output of the cement industry is directly linked to the state of the construction activity and is therefore considered that it closely tracks the overall economic situation (CEMBUREAU, 1999). As shown in Figure 8 cement production has significantly increased since 1960 in all world regions and particularly in Asian countries.

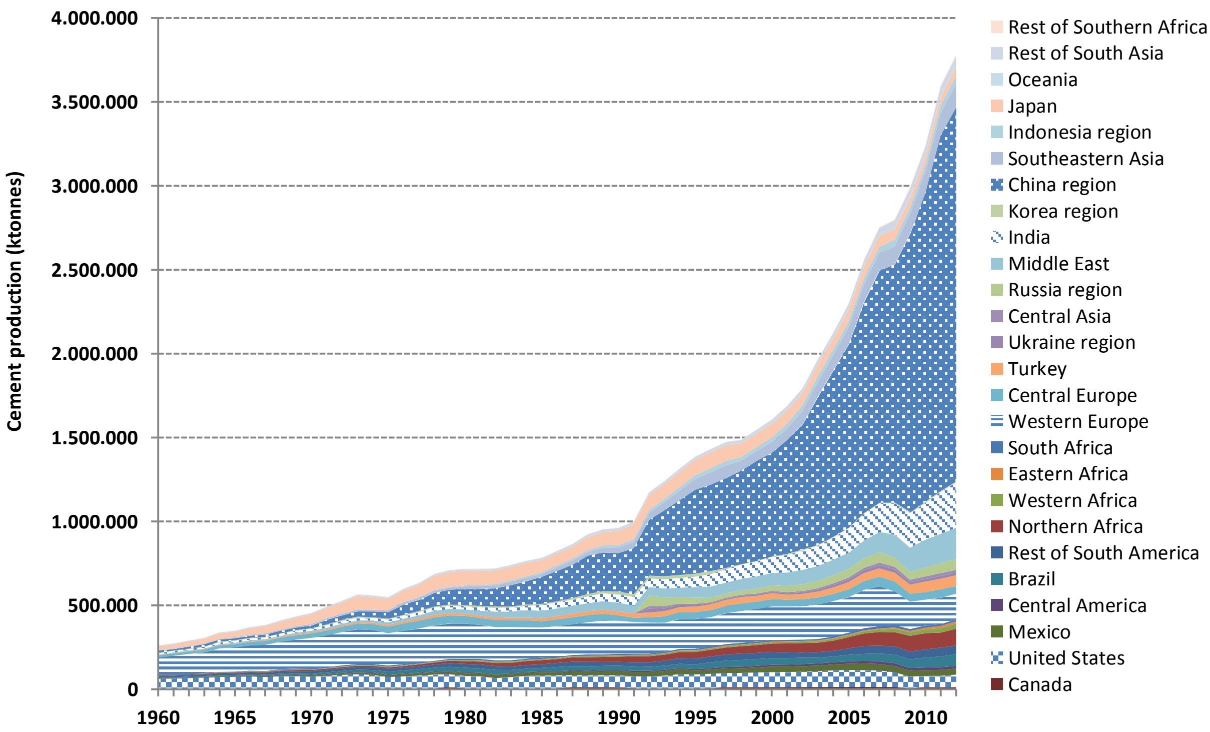


Figure 8 Cement production in the different world regions from 1960 to 2012 (based on USGS, various years)

In 2012 cement production reached 3,850 million tonnes (USGS, 2012). China alone accounted for 58% of global production.

[7] The University of Utrecht plans to publish a summarized version of the cement modelling guide in a peer reviewed article, along with results of implementation in the IMAGE and POLES model.

The cement industry is one of the five most energy-intensive industries, accounting for 11% of global industrial energy consumption[8] (see Figure 9). In 2009, the cement industry consumed 11 EJ of which most is fuel (IEA, 2011).

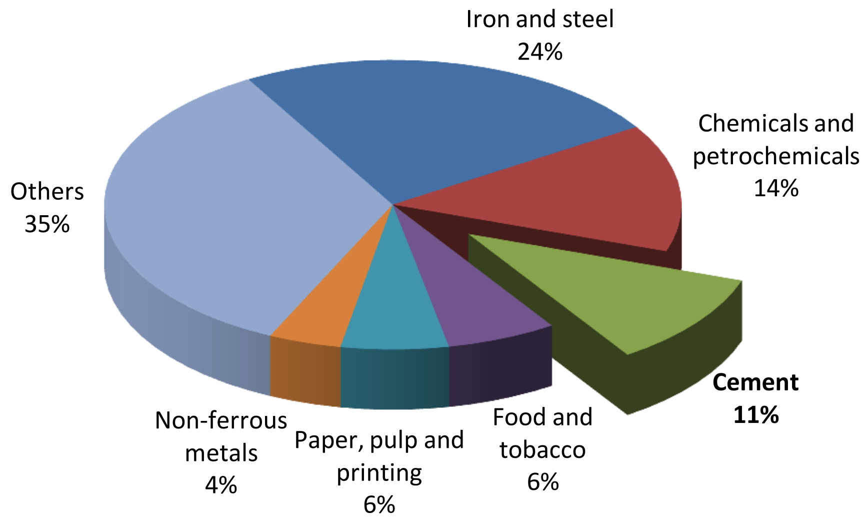


Figure 9 Global industrial energy consumption breakdown per industrial sub-sector in 2009 (based on IEA, 2011). The total final energy use includes the energy use in coke ovens and blast furnaces and excludes the energy use for feedstock purposes

The cement industry is also a significant greenhouse gas emitter. In 2009 2.3 $GtCO_2$ were emitted into the atmosphere (IEA, 2012); about 1.1 $GtCO_2$ were energy related and 1.2 $GtCO_2$ were process related released during the calcination of clinker.

The figure below shows the CO_2 emissions breakdown of the various industrial sub-sectors in 2010. The cement industry is the second most CO_2-intensive industry following the iron and steel industry. In 2010 cement production was responsible for about 26% of global industrial CO_2 emissions.

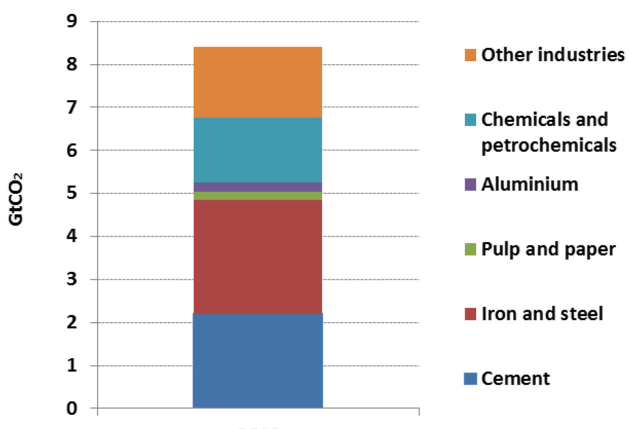


Figure 10 Global industrial CO_2 emission breakdown per industrial sub-sector in 2010 (IEA, 2012)

[8] In 2009 the global industrial energy consumption was 105 EJ (including the energy use in coke ovens and blast furnaces and excluding the energy use as feedstock) (IEA, 2011).

Improving the way the industrial sector is modelled in IAMs is of major importance as it will help to more accurately estimate the regional greenhouse gas (GHG) mitigation potentials and will lead to a better evaluation of the variety of energy policies that could be implemented. In this effort, the improvement of the way the cement industry is currently modelled in IAMs has been identified as a key starting point. This is because the cement industry except from a major industrial energy consumer and GHG emitter is also an industry characterized by limited complexity and can therefore be easier incorporated in existing IAMs than other industrial sub-sectors.

Its limited complexity is due to a number of factors. Most of the cement is consumed in a single sector: the construction sector. Therefore, the entire cement consumption could be linked to the construction activity. In addition, trade is limited as cement is mainly consumed in the country of production. Moreover, the cement manufacturing process is common to all cement plants (although the raw materials or additives used could vary) composed of three main process steps that consume the majority of the energy used: i) raw materials preparation ii) clinker making, and iii) finish grinding. In Appendix B the cement modelling guide developed by Katerina Kermeli of the University of Utrecht to guide IAMs in modelling cement energy and GHG emissions projections can be found.

3.4. Iron and Steel sector modelling

Author: Katerina Kermeli, University of Utrecht

3.4.1. Introduction

The iron and steel industry is one of the most energy consuming and greenhouse gas (GHG) emitting industries. It is estimated that in 2009 steel production was responsible for 24% of industrial energy consumption and 32% of industrial GHG emissions (IEA, 2011). The steel industry generates on average 2.3 $GtCO_2$ that corresponds to roughly 7% of anthropogenic CO_2 emissions (IEA, 2012). Following its importance as an industrial sector, several iron and steel models have been developed (Corsten, 2009; Crompton, 2000; Gielen and van Dril, 1007; Neelis and Patel, 2006; Pardo et al., 2012; Wang et al., 2007) that aim to determine the energy savings potentials and the role of different mitigation options on the limitation of climate change.

The more aggregated energy models and Integrated Assessment Models (IAMs) can have a representation energy scenarios for the iron and steel industry. Some of the models are quite detailed and use some bottom-up information such as different GHG mitigation options and different steel production processes while others are less detailed. The less detailed models determine the energy use with the use of production functions.

The driver mainly used to project steel demand in IAMs is Gross Domestic Product (GDP). This is done by generating functions based on the historic correlation of GDP per capita and steel intensity (defined as steel consumption in kg per GDP). Historically, these two variables relate to each other through an inverted U-shape curve, where steel intensity decouples from GDP per capita growth at higher values. (Neelis and Patel, 2006)

In this research, an effort will be made to identify non-monetary drivers that have a physical relation to steel consumption. Initially, the main steel consuming activities will be identified and indicators capable to represent the level of activity will be determined. An example of a non-monetary driver is m^2/capita of residential and non-residential buildings that drives the steel consumption in the construction industry. This will be followed by the analysis of the historical relationship between the identified non-monetary drivers and steel use. Finally, their use as new drivers in projecting steel demand will be assessed.

It has been argued (Pauliuk et al., 2013) that steel stocks (steel in use in the form of products) instead of steel flows (i.e. steel consumption and steel production) can better indicate the services that steel provides in an economy, due to the long life time of steel containing products. It is therefore not the annual steel consumption that provides the service to the economy but the steel stocks (Muller et al. 2007). An increase in the annual steel consumption indicates that i) there are higher needs in steel services but also that ii) some of the old steel containing products are retired and need to be replaced. Hence, understanding and capturing the evolution of steel demand and the generation of steel scrap in models will greatly improve their projections.

In addition to identifying non-monetary drivers, this research will also attempt to develop a modeling approach for steel demand that takes into account the lifetime of steel products and that focuses on steel stock evolution instead of steel flow evolution.

3.4.2. Background of the Iron and Steel Industry

Steel due to its characteristics and wide versatility has found many applications in almost every part of daily life. It is extensively used in the construction of buildings, bridges, roads and railways, vehicle manufacture, energy generating technologies, energy delivery, and the containment of foods and beverages.

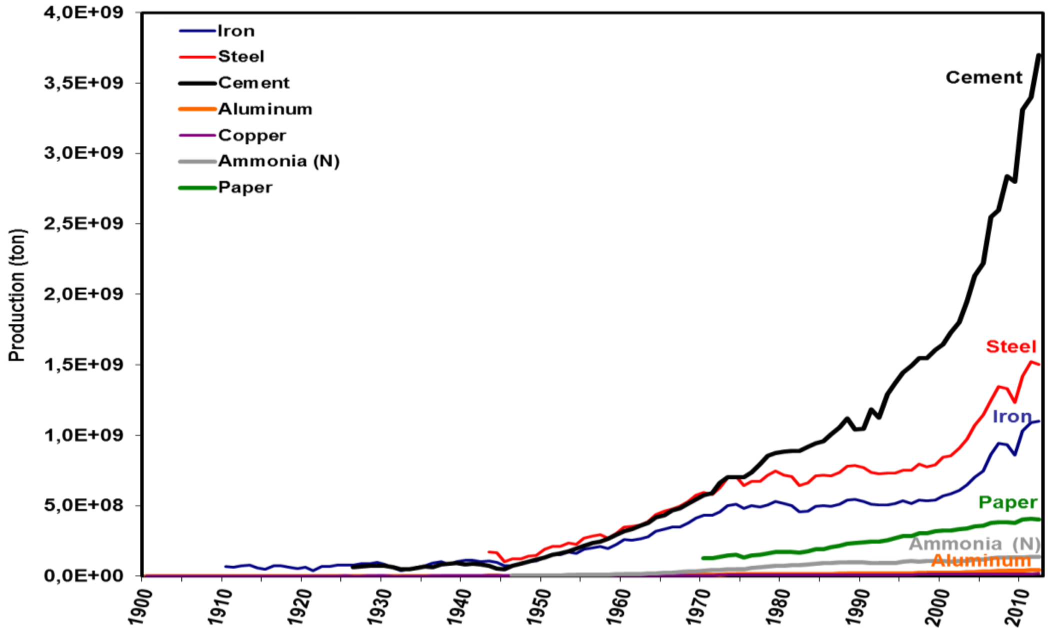


Figure 11 Historical production of some of the most energy intensive industrial products

Following cement, steel comprises one of the most widely used materials (see Figure 11). In 2010, steel production globally overcame the 1.4 Mtonnes. That is double the amount of steel produced in 1980. This is mainly the result of the increased steel consumption in China (see Figure 12).

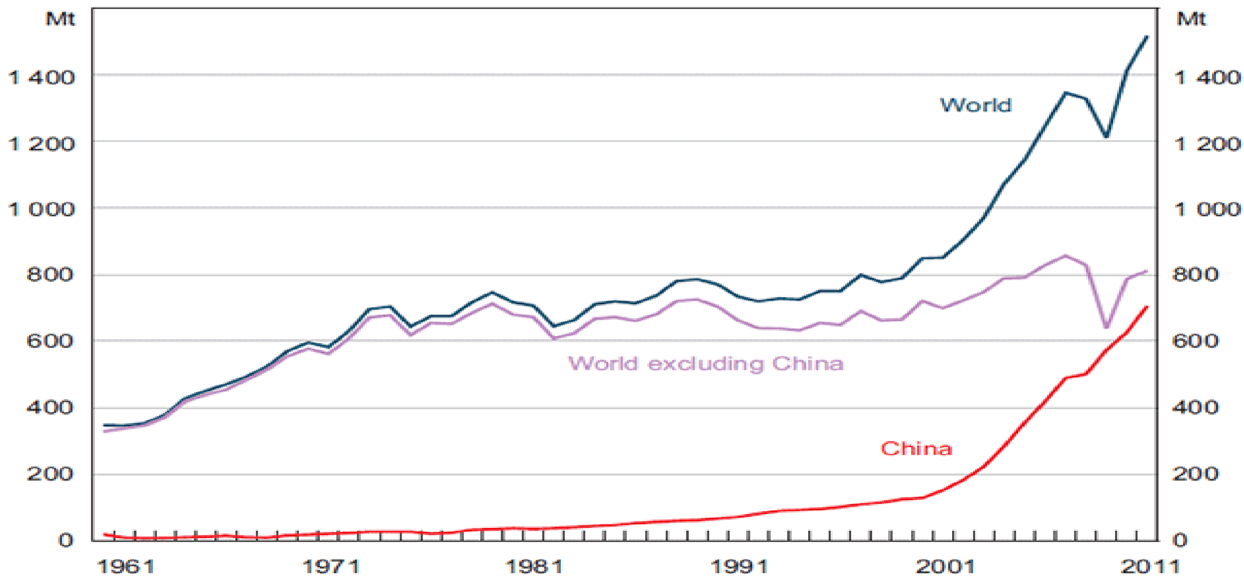


Figure 12 World steel production (Conolly and Orsmond, 2011)

Production routes

The iron and steel industry produces a variety of products such as ingots, slabs, rolls, sheets etc. There is only a limited number of production processes used which are presented in Figure 13. These processes can be divided into:

- ***Primary steel making***; where a blast furnace (BF) and a basic oxygen furnace (BOF) are used with iron ore as the main raw material, and
- ***Secondary steel making***; when an electric arc furnace (EAF) is used with the main raw material being steel scrap.

Primary steel can also be manufactured by directly reducing iron ore (DRI) in a shaft furnace. This technology is however not as commonly used as the other two. In 2009 only 6% of iron produced globally was produced with the DRI process. Most of the DRI was produced in India and Middle East (Worldsteel, 2011).

Primary steel making can be divided into three main steps; raw material preparation, iron making and steel making. In secondary steel making there are only two steps; that is raw material preparation and steel making.

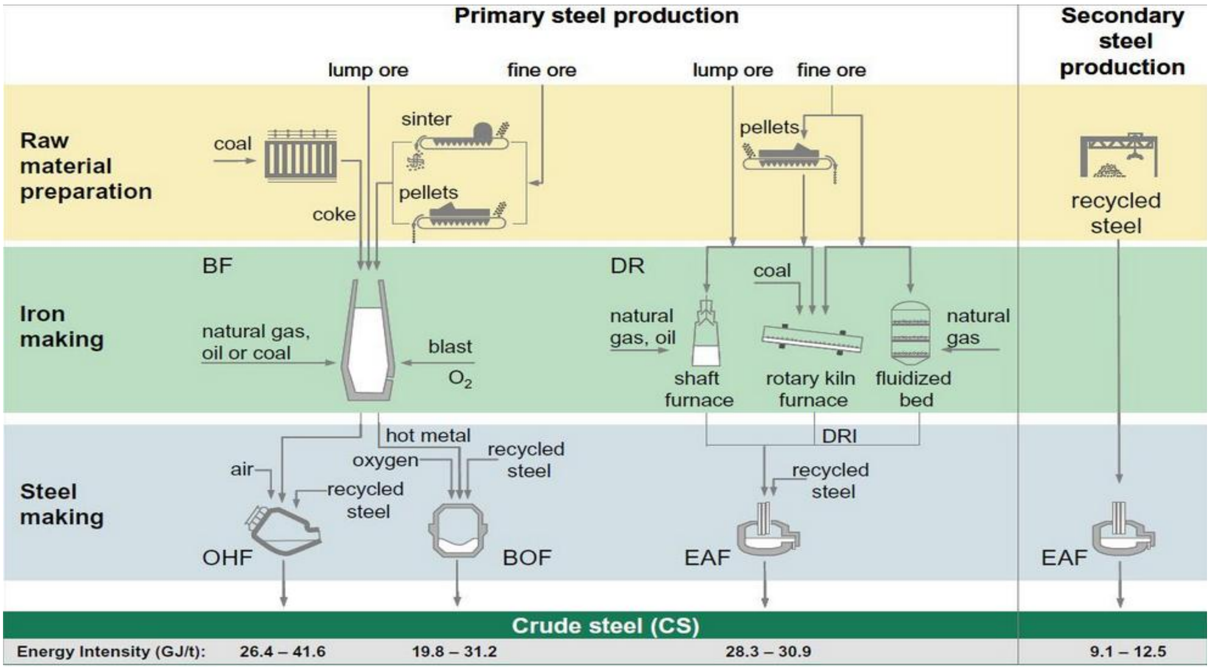
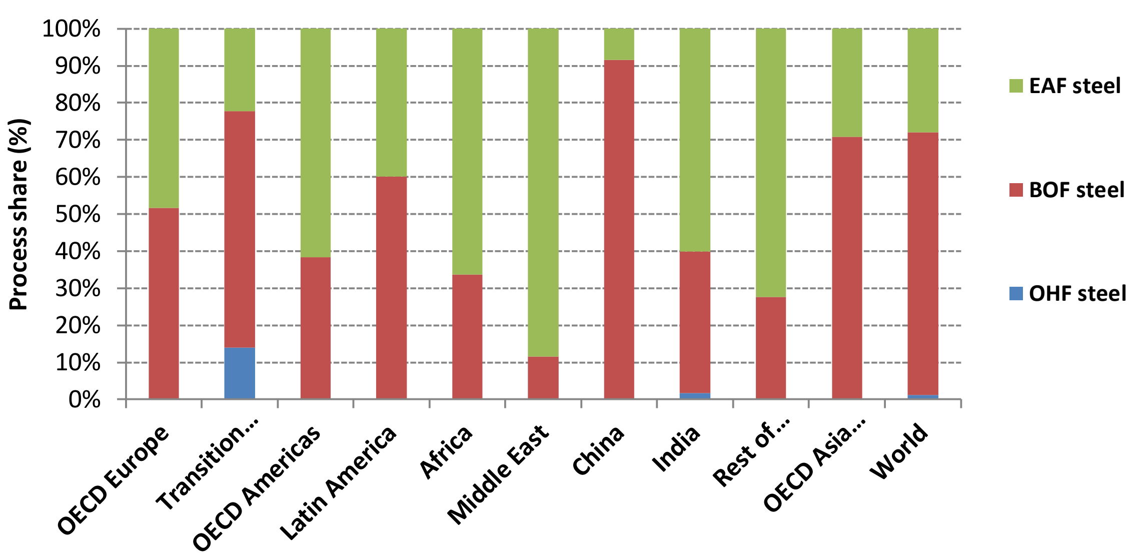


Figure 13 Steel making processes and typical energy intensities (Worldsteel 2008)

Steel making is very energy intensive. The energy intensities of the primary production route can range between 19.8-41.6 GJ/tonne steel. However, when scrap is used as the main raw material (secondary production route) 3-4 times less energy is needed. The energy use in the secondary production route ranges between 9.1 and 12.5 GJ/tonne steel.

Figure 14 shows the processes used for steel production in the different world regions. In 2009 about 30% of steel was produced from scrap.

Figure 14 Shares of the primary and secondary production routes in 2009 per region (based on Worldsteel, 2011)



Steel consumption

There are many types of steel products. They have all been developed in order to satisfy the needs in the housing, automotive, domestic appliances and other industries. The steel consumption can be broken down into activity segments. As shown in Figure 15, about 50 % of steel produced globally is consumed in the construction sector while the automotive, the metals and the mechanical machinery sectors also account for a considerable share.

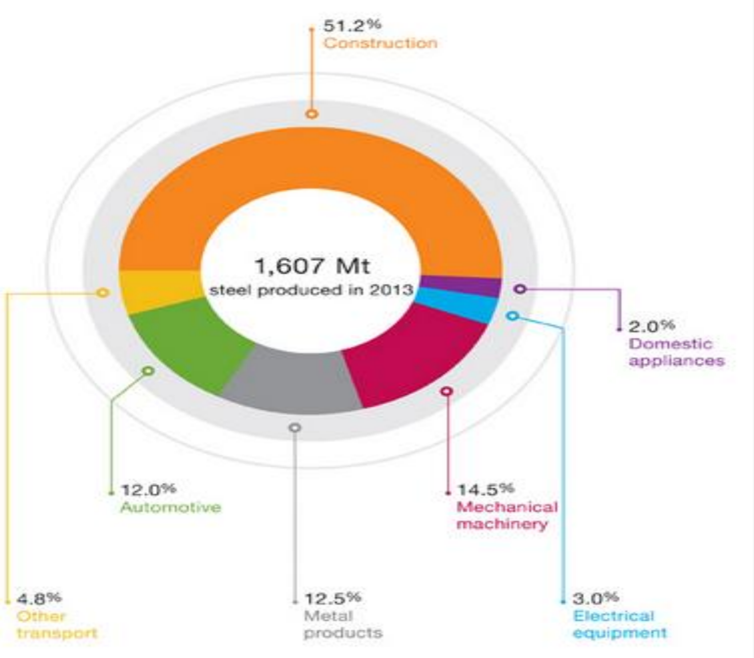


Figure 15 Global steel consumption per activity segment (Worldsteel, 2015)

3.4.3. Main modeling challenges

Making projections of global GHG emissions and final energy use of the steel industry can be challenging due to a number of reasons.

Two production routes

Steel production is divided into two main production routes; the primary and the secondary route. To determine the share of the secondary route, the availability of steel scrap will need to be defined first. Scrap availability will depend on the age and the retirement rates of current steel stocks.

Limited sectorial steel consumption data

Steel is consumed in a variety of sectors (see Figure 15). However, information on steel consumption per different sector (e.g. construction, automotive) and per country is scarce, making it hard to understand where steel is actually consumed.

Trade

Steel is a material that is widely traded between countries/regions. Semi-finished and finished steel products are traded across countries. This is known as direct trade. However, indirect steel trade also takes place; that is the trade of steel containing products such as cars and household appliances. Figure 16 shows the significance of direct and indirect trade.

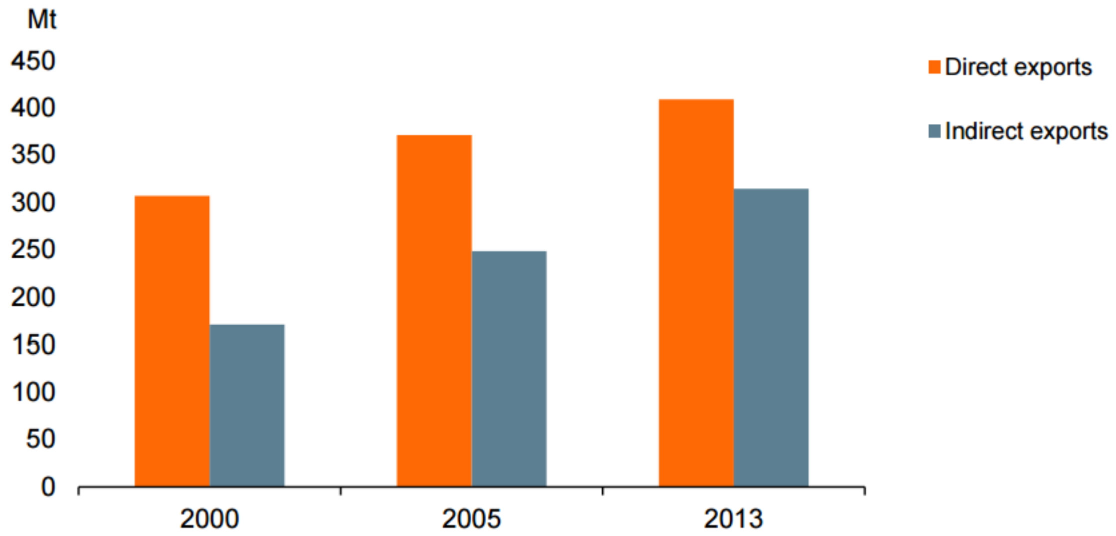


Figure 16 Global direct and indirect trade in 2000, 2005 and 2013 (Worldsteel, 2015)

3.4.4. Research paths

The initials efforts made under the ADVANCE project for improving the way the steel demand is currently modeled in IAMs included the identification of non-monetary drivers (Scherbinski, 2015). Several non-monetary drivers have been assessed, such as building floor area, number of new buildings, weight of concrete reinforcing bars, total rail length, total road length, number of cars produced and number of cars per capita. However, due the limited data availability on the sectorial steel demand per country this approach did not yield sufficient conclusions as to which non-monetary drivers could be used to better project steel demand. Therefore, more approaches are currently being considered:

Under the ADVANCE project, an attempt will be made to develop a modeling approach for steel demand that takes into account the lifetime of steel products and that focuses on steel stock evolution instead of steel flow evolution. In his research, Pauliuk et al. (2013) estimated the amount of steel in use (steel stocks) in 200 countries in the period 1700-2008. The steel stock estimates are split into four steel consuming sectors i.e. construction, transportation, machinery and products. These estimated data will be used along with the estimated age distribution of steel stock to identify how much steel is actually required for an economy to achieve high economic growth. This approach will give us the possibility to investigate at which steel stock levels saturation is achieved and when steel consumption is expected to slow down. The final method that will be used in this approach is currently under consideration.

In case the above approach proves unable to yield important conclusions due to e.g. limitations in data availability, and if there are no significant time constraints, the following approach can also be considered. By linking the buildings and transportation modules to the iron and steel industry modules the degree of alignment within the models could be assessed. For example if a model projects that under a certain scenario the construction activity of e.g. buildings slows down it cannot be that steel consumption for construction purposes increases.

This is possible since a number of IAMs provide information on how the household construction activity will develop in the future as they supply information on future floorspace area. By using a steel intensity factor (e.g. kg of steel/m^2 of residential floor area) the future steel demand for building construction purposes can be projected. A similar method can be followed for the transportation sector. An increase in car use or aviation can be translated into steel use by applying steel intensity factors (e.g. kg of steel/car and kg of steel/plane).

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3.5. Description of model development cement sector in IMAGE

Author: David Gernaat, PBL Netherlands Environmental Assessment Agency

Improving the modelling of the cement sector is important to more accurately assess greenhouse gas emissions and their mitigation potential on a global and long-term time scale. This modelling improvement creates better tools to assist in the process of developing adequate energy and climate related policies. The cement sector has grown rapidly and reached nearly 4000 million tons in 2012 (USGS, 2012). Much of this growth comes from China that accounted for 58% of global production. The cement industry is one of the five most energy-intensive industries, accounting for 11% of global industrial energy consumption.

The ADVANCE model development of the cement sector in the IMAGE model focuses on improvements of both the demand projections and the technological clinker making options. Here we describe the implementation of both improvements and briefly show the impact on the results.

3.5.1. Demand modelling

The cement demand is modelled using a non-linear regression model that describes the correlation between GDP per capita and material as an inverter U-shaped curve. This model generally states that the cement demand follows the growth in income per capita. Regions that move towards industrialization cement intensity (t/$) increases but as income increases, the demand saturates after which the cement intensity levels follow a decreasing trend (see Figure 17). Equation 2 from the modeling guide to cement was used in the model implementation.

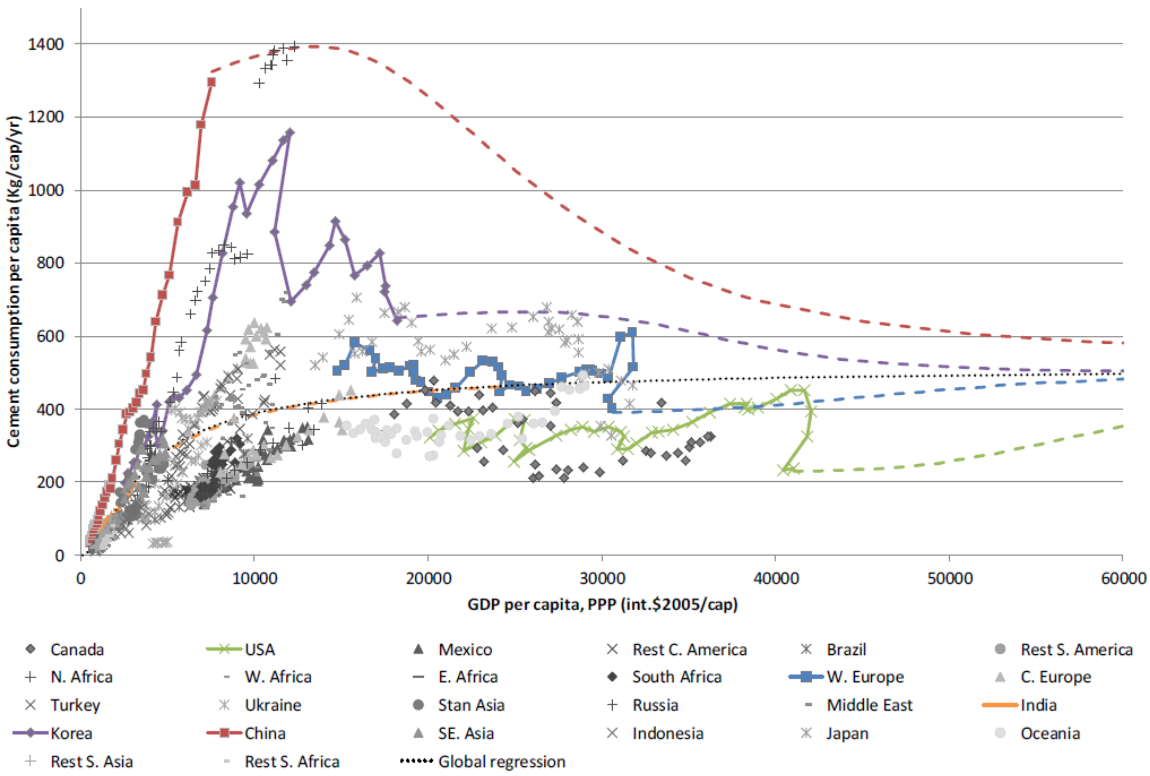

Figure 17 – Cement demand using an inverted U-shaped non-linear regression model

3.5.2. Technological modelling

Regarding the technological options in the IMAGE model, it already described four different clinker making production technologies, summarized in Table 3. The model described four production technologies, two standard options (normal and efficient) and two options with carbon capture technology. Each option is characterized by different levels of investment, energy use, improvement rates and carbon capture percentages.

Table 3 – Original clinker making production technologies in IMAGE

	Investment cost (1995$)/ tonne production/year	Annual O&M cost	Energy us GJ/ tonne	Energy efficiency improvement rate	CO2 not captured
Normal Dry	193	10	3.9	0.998	100%
Efficient Dry	263	10	2.9	0.994	100%
Efficient + on-site-CCS	326	10	3.2	0.994	45%
Efficient + oxy-comb CCS	558	15	8.1	0.994	14%

The modelling guide to the cement industry describes detailed description of more than 25 different efficiency improvement technologies that include energy savings (GJ/tons) and investments ($/tons) per option. To sensibly use of this information we condensed these to three technological options that describe low, medium and high efficiency options that have specific characteristics regarding costs and energy use (see Table 4).

Table 4 – New clinker making production technologies in IMAGE

	Investment cost (1995$)/ tonne production/year	Annual O&M cost	Energy us GJ/ tonne	Energy efficiency improvement rate	CO2 not captured
Normal Dry	193	10	3.9	0.998	100%
Normal Dry - Low efficiency	195	10	3.5	0.996	100%
Normal Dry - Med efficiency	202	10	3.3	0.995	100%
Normal Dry - High efficiency	282	10	2.8	0.994	100%
High efficiency + on-site-CCS	345	10	3.15	0.994	45%
High efficiency + oxy-comb CCS	577	15	8.06	0.994	14%

3.5.3. Results

The modelling updates have consecutively been tested and assessed in the context of a baseline (SSP2) and a scenario that is consistent with a 2 degree climate target. Figure 18 and 19 shows the results of the old (left) and new (right) model in term of Mtons clinker production per technological option.

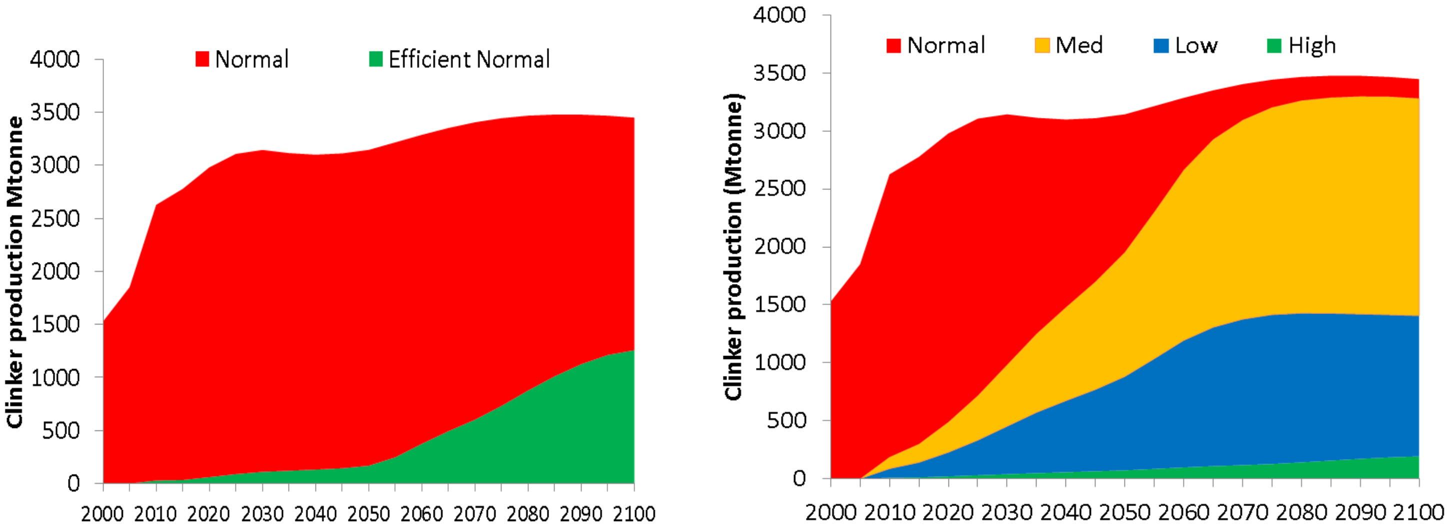

Figure 18- Old (left) and new (right) technological development in the cement sector in a baseline scenario (SSP2)

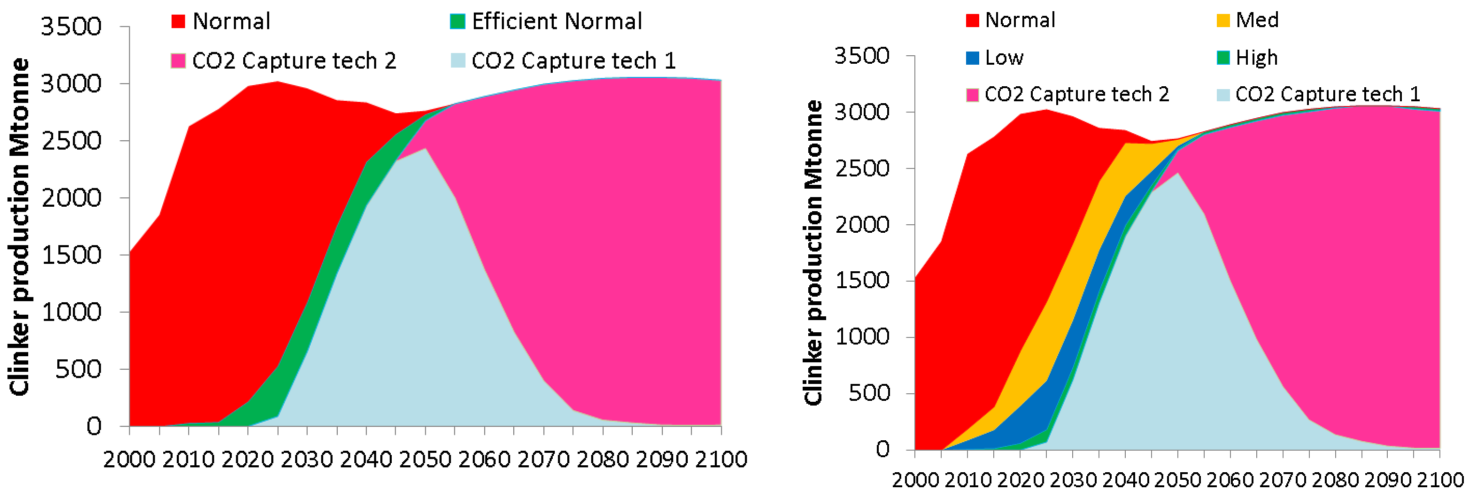

Figure 19 - Old (left) and new (right) technological development in the cement sector in a 2 degree scenario

The results show more technological flexibility, especially in the short term. While the previous model shows growth of the efficient technology by mid-century onwards, the new model shows development of the low and medium technologies already in the short term. A similar situation can be seen in the 2 degree scenario.

The inclusion of more detailed technological information in the cement sector model introduced a higher degree of technological flexibility that eventually results in lower short term energy use, as can been seen in Figure 20.

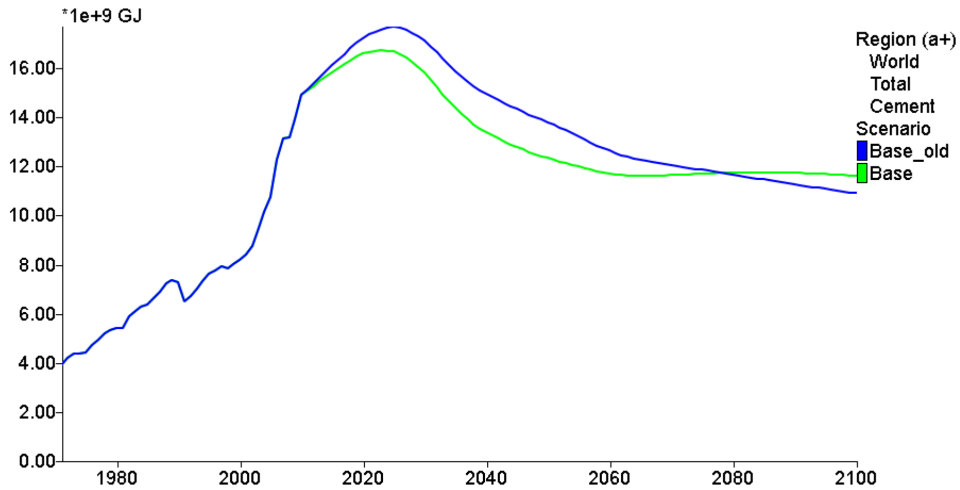

Figure 20 - Original (blue) and new (green) energy use of the cement sector

Appendix A: IAM model description

Asia-Pacific Integrated Model – Computable General Equilibrium (AIM/CGE).

The AIM/CGE model, developed by the National Institute for Environmental Studies in Japan, has been widely used for the assessment of climate mitigation and impact (e.g.,(Fujimori, Kainuma et al. 2014; Hasegawa, Fujimori et al. 2014; Hasegawa, Fujimori et al. 2015)). The AIM/CGE model is a one year step recursive-type dynamic general equilibrium model that covers all regions of the world. AIM/CGE has an option to be used as country mode (Thepkhun, Limmeechokchai et al. 2013).

The production sectors are assumed to maximize profits under multi-nested Constant Elasticity Substitution (CES) functions and each input price. Energy transformation sectors input energy and value added as fixed coefficients of output. They are treated in this manner to appropriately deal with energy conversion efficiency in the energy transformation sectors. Power generation values from several energy sources are combined with a Logit function. This method is adopted in consideration of energy balance since the CES function does not guarantee a material balance. Household expenditures on each commodity are described by a Linear Expenditure System (LES) function. The Armington assumption is used for trade, and the current account is assumed to be balanced.

Instead of using typical CES function, there is an option to couple very detailed technological information for energy end-use sectors (more than 300 kinds of technologies) adopted in AIM/Enduse which is bottom-up type model (Fujimori, Masui et al. 2014). To assess bioenergy and land use competition appropriately, agricultural sectors and land use categories are also highly disaggregated (Fujimori, Hasegawa et al. 2014).

Dynamic New Earth 21 plus (DNE-21+).

DNE21+ is an energy-related CO_2 emission assessment model developed by the Research Institute of Innovative Technology for the Earth (RITE) in Japan. The model is the key assessment model of RITE's integrated assessment framework, and an optimization type of bottom-up linear programming model, highly technologically detailed, where the global costs are minimized when policies such as carbon tax, emission cap, and energy standard are applied (Akimoto 2008; Akimoto 2010) . The salient features of the model include (1) analysis of regional differences with fine regional segregation (The world is divided into 54 regions.), (2) a detailed evaluation of global warming measures by modeling around 300 specific technologies that can be used to counter global warming, and (3) explicit considerations on facility transition for the specific technologies over the entire time period. Historical capital stocks by energy efficiency levels of the specific technologies are assumed considering regional current differences in energy efficiency (Oda 2012).

In DNE21+, the industrial sector is broken down into the iron and steel, cement, pulp and paper, aluminum, some chemicals (ethylene, propylene, and ammonia) and the others sub-sectors. All sub-sectors are modelled following a bottom-up approach except for the others subsector which is modelled in a top-down way (Oda 2007). The future material demand is estimated based on historical relationships between production, consumption, imports, exports and GDP and population levels. Furthermore, availability of steel scrap is also considered for developing future crude steel scenario (Oda 2013).

Global Change Assessment Model (GCAM).

GCAM, previously known as MiniCAM, is an integrated assessment model developed by the Joint Global Change Research Institute (JGCRI 2014), at the Pacific Northwest National Laboratory. It links the world's economy, energy, agriculture, land use and technology systems together with a climate model to assess a variety of climate change policies (EPA 2013; GCAM 2015). It has been used in a number of climate change assessment and modeling activities such as the Energy Modeling Forum (EMF), the U.S. Climate Change Technology Program, and the U.S. Climate Change Science Program and IPCC assessment reports. GCAM is freely available as a community model (JGCRI 2014).

In GCAM, the energy demand in the industrial sector is derived from a constant elasticity equation where energy demand is indexed to GDP change (Brenkert A. 2003). The demand for cement is driven by GDP and the demand for fertilizers is determined by the land use module. For the remaining industrial sectors, GCAM models a single homogeneous industrial good.

Imaclim-R.

The Imaclim-R model (Waisman, Guivarch et al. 2012) is a multi-region and multi-sector model of the world economy. It combines a Computable General Equilibrium (CGE) framework with bottom-up sectoral modules in a hybrid and recursive dynamic architecture. It is developed by the Centre International de Recherche sur l'Environnement et le Développement (CIRED). Imaclim-R studies the relationships between energy systems and the economy, and can be used to assess the feasibility of climate change strategies and the transition options towards a global low-carbon future (ADVANCE 2015). In Imaclim-R, industrial energy use is not modeled with disaggregated technologies. The energy intensity of the industry sector decreases over time due to price-induced energy efficiency improvements and due to new installed capacities characterized by higher efficiencies. In the industrial sector, structural change (a decrease in the activity of the heavy industries as compared to the manufacturing industries) leads to an additional decrease in energy intensity. To represent saturation of industrial goods consumption, the income elasticities of consumption of industrial and agricultural goods are assumed to decline with increasing per-capita income (Waisman, Guivarch et al. 2012).

Integrated Model to Assess the Global Environment (IMAGE).

The Integrated Model to Assess the Greenhouse Effect (IMAGE), was developed by PBL Netherlands Environment Assessment Agency. The IMAGE model, is an IAM that simulates the environmental consequences of human activities in industry, housing, transportation, agriculture and forestry worldwide. It represents large scale and long term interactions between human development and natural systems to gain insight into the processes of global environmental change, assesses options for mitigation and adaptation, and identifying levels of uncertainty. A great number of global studies, such as the IPCC Special Report on Emissions Scenarios (SRES), the UNEP Third Global Environment Outlook (GEO-3) and the Millennium Ecosystem Assessment (MA) have used the simulated results from IMAGE (Stehfest 2014) (Bouwman 2006).
In the industrial module of IMAGE, the final energy demand is modelled as a function of changes in population, economic activity and energy efficiency. The change in energy-intensity (i.e. energy units per monetary unit) is assumed to be a bell-shaped function of the level of per capita activity (i.e. sectoral value added or GDP). The industrial energy intensity can decrease due to autonomous energy efficiency improvements but also due to increased energy prices. To model the decrease in industrial energy intensity two multipliers are used; 1) an Autonomous Energy Efficiency Increase (AEEI) multiplier which is linked to the economic growth rate, representing energy efficiency improvements that occur as a result of technology improvement independent of energy prices, and 2) The Price-Induced Energy Efficiency Improvement (PIEEI) multiplier which is used to describe the effect of (rising) energy costs on energy intensity. The PIEEI multiplier is calculated with the use of a sectoral energy conservation supply cost curve and end-use energy costs.

The material demand (in tonnes of product) and production technologies for two industrial sub-sectors; the iron and steel and the cement industrial sub-sectors are explicitly modelled. The material demand is a function of the economic activity and material intensity. Once the consumption level has been determined, a material production model simulates how to fulfill the demand for steel and cement, taking into account trade, stock turnover, recycling, and competition between different steel and cement production technologies The material production is met by different steel and cement producing technologies, which are characterized by investment cost, fuel costs and energy requirements. For all the remaining industrial sub-sectors, the energy demand is modeled based on activity data, structural change, and the AEEI and PIEEI, as described above.

Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE).

The MESSAGE IAM, is a technology detailed hybrid model (energy engineering partial equilibrium model linked to general equilibrium model), developed by the International Institute for Supplied Systems Analysis (IIASA) for energy scenario construction and energy policy analysis (ADVANCE 2015). Its results have been used in major international assessments such as the Intergovernmental Panel of Climate Change (IPCC) and the Global Energy Assessment (GEA)(IIASA 2012).

The industrial sector in MESSAGE is not disaggregated into the various industrial sub-sectors. The total industrial energy demand is generated using regression analysis with the use of historical GDP/capita and final energy use data as well as GDP and population projection data (ADVANCE 2015).

Prospective Outlook on Long-term Energy Systems (POLES).

The POLES model is an econometric, technology detailed, partial-equilibrium model initially developed by the Institute of Energy and Policy and Economics (IEPE, now known as LEPII-EPE), Enerdata and the Institute for Prospective Technological Studies (IPTS) (JRC/IPTS 2010). POLES is primarily used for energy demand and supply projections, analyzing greenhouse gas emission reduction pathways, and assessing the impacts of technological change. It has been used for policy evaluation purposes by the EU-DG research, DG Environment, DG TREN, the French Ministry of Ecology and the Ministry of Industry (Criqui 2009).

The industrial sector is disaggregated into the iron and steel, non-metallic minerals (cement and glass), chemical (including feedstock use) and the rest of the industry sub-sectors (including non-energy use) (JRC/IPTS 2010; Criqui 2009) and it entails detailed technological modules for the sub-sectors iron and steel, aluminium and cement (Russ, Wiesenthal et al. 2007). The industrial final energy demand depends on energy costs, either income or sub sector specific national value added, and autonomous technological trends (JRC/IPTS 2010; Criqui 2009). Improvements in energy intensity depend as well on long-term price elasticities.

TIMES Integrated Assessment Model – University College London (TIAM-UCL).

TIAM was developed by the Energy Technology Systems Analysis Programme (ETSAP). The ETSAP-TIAM model has been used for the analysis of different climate change mitigation policies (Anandarajah 2011). The TIAM-UCL energy systems model is a global optimization model that investigates decarbonisation of the global energy-environment-economy system.

Industrial energy services modeled in TIAM-UCL are chemicals, iron and steel, non-ferrous metals, non-metals, pulp and paper and other industries. The material demand is modeled for iron and steel, pulp and paper and non-metals, while in the remaining industrial sub-sectors the total energy demand is related directly to economic activity. The development of industrial sectoral growth rates are geared to GDP. A shift in the GDP composition towards the service sector is implied, so that agriculture and industry will become less important for the whole economy in the future. Demand drivers (population, GDP, etc.) are obtained externally, via other models or from other sources (Anandarajah 2011).

TIAM-UCL models a large number of technologies in the industrial sector to meet the energy-service demands (divided into steam, process heat, machine drive, electro-chemical processes and other). To satisfy every energy-service of each industry, the existing technologies, characterized by an efficiency, an annual utilization factor, a lifetime, operation costs, and six seasonal share coefficients are represented in the model for the base year. New technologies progressively replace the existing ones. Regional specific hurdle rates are applied to new technologies varying from 10% for developed countries to 20% for developing countries.

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Appendix B: Cement modelling guide supplementary

Katerina Kermeli

1. The cement production process

Figure 21 shows the processes involved in cement manufacture; i) quarrying, ii) raw materials preparation, iii) clinker burning (limestone calcination) and iv) cement grinding. Clinker is the main component of cement and is produced with the calcination of limestone in cement kilns. Clinker production comprises the most energy intensive step in cement manufacture, accounting for about 90% of the overall energy use. The clinker production process is also the most CO_2 intensive process in cement production as except from the CO_2 emitted from fuel combustion, CO_2 emissions inherent to the clinker production process released during the calcination of limestone are also emitted, commonly referred to as process CO_2 emissions (IPCC, 2006)[9].

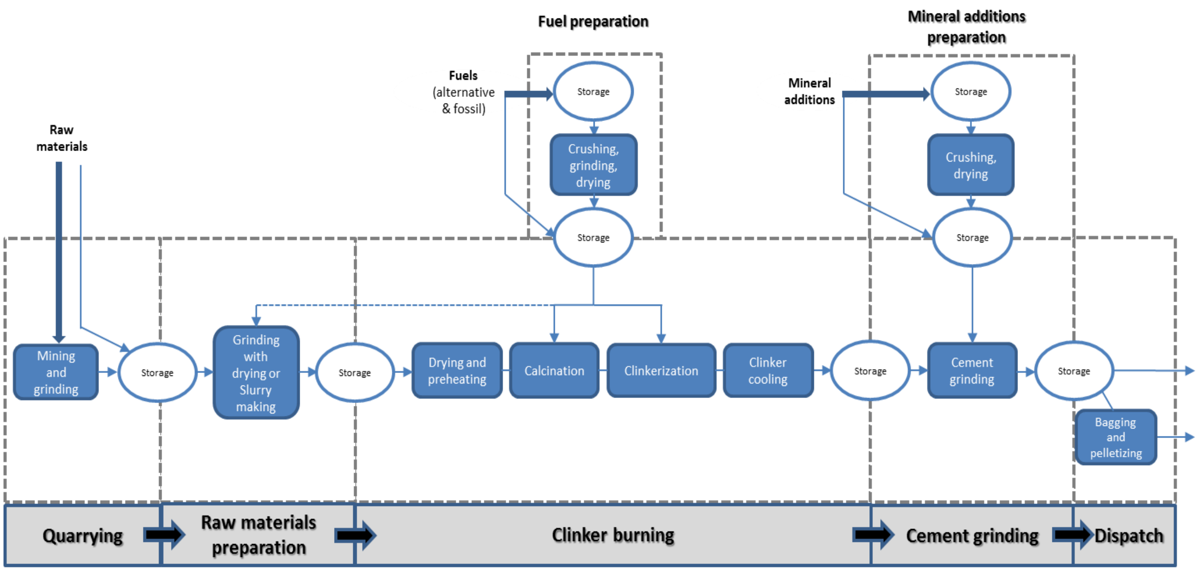

Figure 21 The cement production process (based on CEMBUREAU, 1999)

Raw material quarrying

The main raw materials needed for the manufacture of cement are limestone, chalk, clay and shale. Limestone provides the needed calcium oxide and some of the other oxides, while clay, shale and other materials provide most of the silicon, aluminium and iron oxides. The raw materials are extracted from quarries which are mostly open-pit. The cement plants are most usually situated close to the limestone or chalk quarries. After extraction, the raw materials are crushed, pre-homogenized, ground and proportioned so that the resulting mixture has the desired fineness and chemical composition to be fed in the cement kiln (Worrell et al., 2013).

[9] The typical calcination reaction is : $CaCO_3$ + heat → $CaO + CO_2$

The power consumption for crushing can range between 0.4 and 1.0 kWh/tonne of raw material (Chatterjee, 2004).

Raw material preparation

After the primary and secondary size reduction, the raw materials are further reduced in size by grinding. There are a variety of grinding technologies used, e.g. ball mills, roller mills and roller presses. The grinding process differs with the type of the kiln used for clinker production. When dry kilns are used, the raw materials are ground into a flowable powder. The typical moisture content of the feed kiln is about 0.5%.

When the raw materials have high moisture content (more than 20%) wet kilns are used in clinker production (IPTS/EC, 2010). In the wet process, the raw materials are ground with the addition of water in ball mills to produce a slurry typically containing 36% water.

Raw material grinding is electricity intensive and can consume 9-32 kWh/tonne raw material (Worrell et al., 2013).

Clinker burning (pyroprocessing)

Clinker production is the most energy-intensive step in cement production, accounting for more than 90% of the total energy use and all of the fuel use. Clinker is produced by pyroprocessing in cement kilns. Cement kilns evaporate the water present in the raw meal, calcine the carbonate, and lastly, form cement minerals (clinker). The produced clinker is then cooled down in coolers.

Clinker is produced with the wet or the dry process. The dry process has lower energy requirements than the wet process due to the lower evaporation needs. To increase the waste heat recovery and thus the overall energy efficiency, dry kilns are equipped with preheater tower systems. The more preheater stages the less energy is consumed. However, when the raw materials or fuel used are very humid, it can be more energy efficient to use fewer preheater stages and use the extra heat for drying (Bolwerk et al., 2006).

More recently, the precalciner technology has been developed in which a second combustion chamber is added between the kiln and the pre-heater system that allows for further reduction of kiln fuel requirements. The most efficient pre-heater, pre-calciner kilns use approximately 2.9 GJ/tonne clinker (IPTS/EC, 2010).

Cement grinding

To produce Portland cement, the cooled cement clinker is ground together with additions (3-5% gypsum to control the setting properties of the cement) in ball mills, ball mills in combination with roller presses, roller mills, or roller presses (Alsop and Post, 1995). To produce blended cements, cement clinker is ground along with other additives, such as granulated blast furnace slag (GBFS), fly ash, natural or artificial pozzolanas and limestone. In some cases these additives need to be dried first.

The electricity use for cement grinding depends on the surface area required for the final product and the additives used. Electricity use for raw meal and finish grinding depends strongly on the hardness of the material (limestone, clinker, pozzolana extenders) and the desired fineness of the cement as well as the amount of additives. Blast furnace slags are harder to grind and hence use more grinding power.

The final product, finished cement is then stored in silos, tested and filled into bags, or shipped in bulk on bulk cement trucks, railcars, barges or ships. Electricity is also consumed for conveyor belts and packing of cement. The total consumption for these purposes is generally low.

2. Modeling energy use and greenhouse gas emissions in cement production

In this section we give a description of the approaches that could be used for modeling the cement industry. In addition, relevant information that could be used in the models such as information on current regional energy intensities, clinker to cement ratios and measures for energy efficiency improvements is also provided, where possible.

Section 3.1 describes two approaches that could be used for modeling the cement demand and cement production. After the cement production is determined, Section 3.2 follows, where a description is given on the way the energy use for cement making could be modelled. Section 0 focuses on the measures that could decrease the energy consumption and therefore the CO_2 emissions, and information is provided on the energy savings potentials and the associated investment costs. Section 3.4 presents the way the greenhouse gas emissions (GHGs) from cement production could be modelled and Section 3.5 presents the ways the clinker to cement ratio could be reduced.

3.1. Modeling the cement demand and production

Most models that simulate the physical demand of cement are based on the historically observed correlation between the economic activity and material intensity and the product demand (e.g. Akashi et al., 2011; Anand et al., 2006; Groenenberg et al., 2005; Pardo et al., 2011).

To increase the understanding of the underlying processes that drive cement demand and construct a more bottom-up type of approach for the forecasting of cement demand developments, the relationship between the historical cement demand in the different construction sectors and the floorspace area of these specific sectors was investigated. Paragraph 1.1.1 shows how cement consumption could be modelled with the use of function relations between cement use and some construction activity indicators and paragraph 1.1.2 shows how cement consumption could be modelled based on monetary indicators.

1.1.1 Cement consumption and construction activity

Cement is consumed in a variety of construction projects mainly divided into the construction of i) residential buildings, ii) non-residential buildings, and iii) infrastructure. Residential buildings include buildings built for housing purposes. Non-residential buildings comprise industrial, commercial, educational, health and other type of buildings not used for residential purposes. Infrastructure includes the construction of roads, bridges, sewage systems etc. Table 5 shows the cement consumption broken down per construction activity in the countries for which data is available.

Table 5 Cement consumption per different construction activity (CEMBUREAU, 2013; USGS, various years; PCA, 2012; BNE, 2011; International Cement Review, 2013)

Country/region	Year	Residential buildings (% of total)	Non-residential buildings (% of total)	Infrastructure (% of total)[2]	Resid. Cement Consumption (ktonnes)	Non-Resid. Cement Consumption (ktonnes)	Infr. Cement Consumption (ktonnes)	Road/highway construction (% of Infrastructure)
United States	1998	22%	27%	51%[1]	22,500	27,000	51,667	
United States	1999	24%	26%	50%[1]	25,000	28,000	53,320	60%
United States	2000	30%	22%	48%	32,000	24,000	51,669	74%
United States	2001	30%	20%	50%	33,000	22,500	55,020	71%
United States	2002	33%	16%	51%	35,000	17,500	53,725	73%
United States	2003	35%	15%	50%	38,000	16,500	55,542	70%
United States	2004	36%	14%	50%	42,000	17,000	58,435	N/A
United States	2005	36%	14%	49%	45,000	17,500	61,230	N/A
United States	2006	33%	14%	53%	41,000	17,000	66,310	N/A
United States	2007	29%	14%	57%	33,000	16,000	63,848	59%
United States	2008	23%	13%	64%	22,000	12,000	61,710	57%
United States	2009	27%	9%	64%	19,000	6,000	45,366	71%
United States	2010	24%	6%	69%	17,000	4,500	48,559	54%
United States	2011	23%	7%	71%	16,500	4,800	51,104	53%
Cuba	2005	22%	43%	35%[1]	225	438	352	N/A
Chile	2006	35%	35%[2]	30%[1]	1,533	1,533	1,314	N/A
Mexico	2006	50%	13%	35%	16,393	4,262	11,475	N/A
China	2006	35%	30%[3]	35%[4]	370,404	317,489	370,404	N/A
Vietnam	2006	20%	N/A	N/A	6,172	N/A	N/A	N/A
Azerbaijan	2006	55%	23%	22%	1,087	455	435	N/A
Israel	2006	50%	17%	33%[1]	1,663	565	1,097	N/A
Czech Republic	2006	20%	45%	35%	883	1,988	1,546	57%
Slovenia	2006	25%	5%	70%[1]	338	68	946	N/A
Serbia and Montenegro	2006	60%	N/A	N/A	1,296	N/A	N/A	N/A
Austria	2006	27%	27%	47%	1,420	1,420	2,485	N/A
France	2006	40%	25%	35%[1]	9,062	5,685	7,768	N/A
Italy	2006	36%	31%	33%[1]	16,579	14,276	15,197	N/A
Germany	2006	37%	29%	34%[1]	10,006	7,842	9,195	N/A
Finland	2006	29%	38%	33%	496	651	565	N/A
Spain	2006	N/A	N/A	45%	N/A	N/A	23,180	N/A
Turkey	2006	66%	17%	17%[1]	23,260	5,824	6,034	N/A
South Africa	2006	60%	25%	15%	7,161	2,984	1,790	N/A

[1] The cement use for the construction of all types of non-residential buildings is not reported. Therefore, the reported cement use in infrastructure projects could also include cement consumption for the construction of some non-residential buildings

[2] Only industrial buildings

[3] Industrial 15% and public facilities 15%

[4] Infrastructure 15% and agriculture 20%

Figure 22 shows the per capita residential cement consumption in relation to the residential floorspace area for the United States. It can be seen, that the cement consumption per capita increases with the floorspace increase.

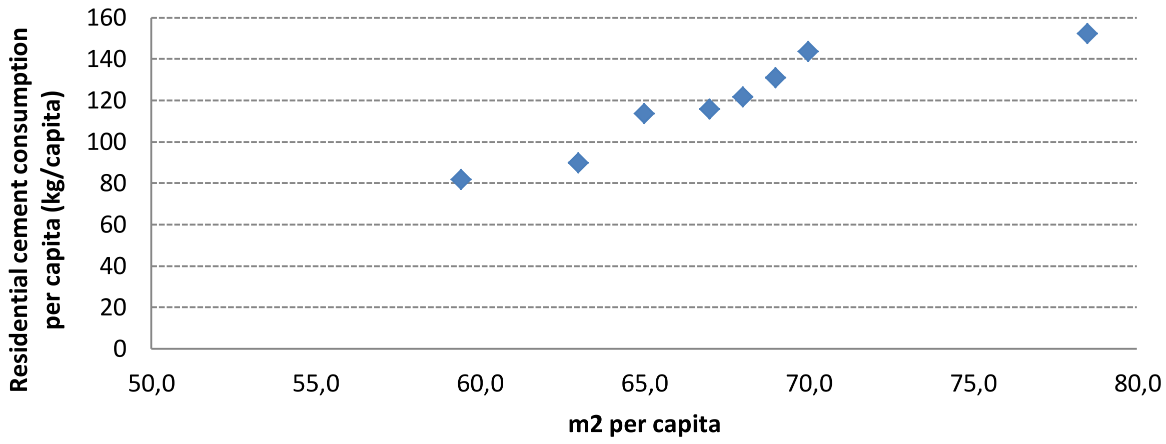

Figure 22 Per capita residential cement consumption and residential floorspace in the United States (period 1998 to 2005)

Based on Table 5 and on information on cement use in the EU countries, the residential cement use is plotted against the average residential floor space area (see Figure 23). In the case of the EU, cement consumption breakdowns per different construction sector do not taken into account the cement use for repair and maintenance purposes. For some countries, the cement use for repairing and maintaining roads, buildings etc. is substantial; Germany (13-40%), Lithuania (41-54%), and Estonia 53% (CEMBUREAU, 2015). However, there is no information on which of the construction activities these cement volumes are consumed.

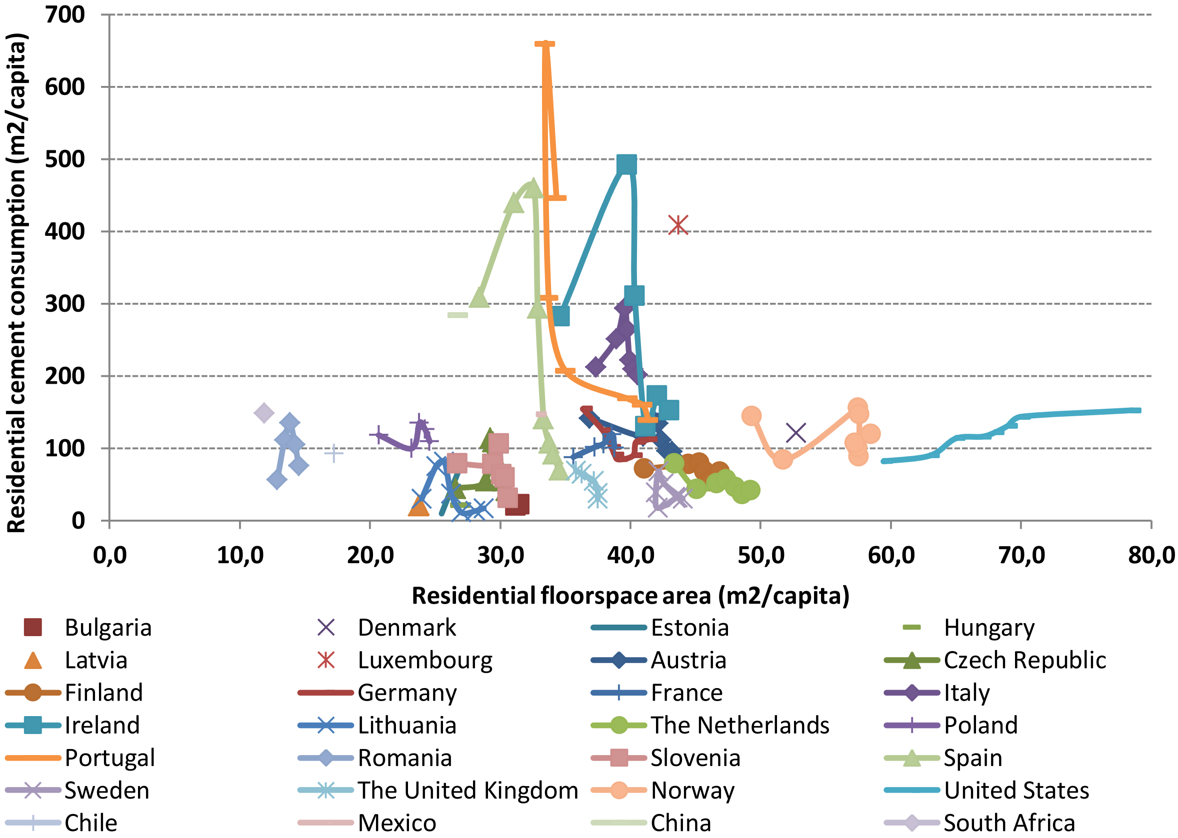

Figure 23 Per capita cement consumption in the residential sector in EU countries (period 2000-2013) and other non-EU (1998-2005)
Sources: CEMBUREAU, 2015; own calculations based on ODYSSEE, 2015

As seen in Figure 23, the U.S. residential floorspace per capita is almost double the floorspace in European countries. The residential floorspace area in the U.S. is one of the largest (76m^2/capita), and then follow Norway (59m^2/capita) and the Netherlands (50m^2/capita). However, the per capita cement consumption in the U.S. is at a similar level. This is mainly due to the fact that in the U.S., while cement is widely used in the construction of residential buildings, wood is another material commonly used. An increasing trend in the per capita cement use can be observed in the early 2000s for many European countries. This is followed by a significant drop in cement use in the late 2000s most probably as an outcome of the slowdown in construction activity during the financial crisis.

Figure 24 shows the correlation between the non-residential cement consumption and the floorspace developments in the United States within the 1998-2008 period. Figure 25 shows the same correlation while also including the years during the financial crisis.

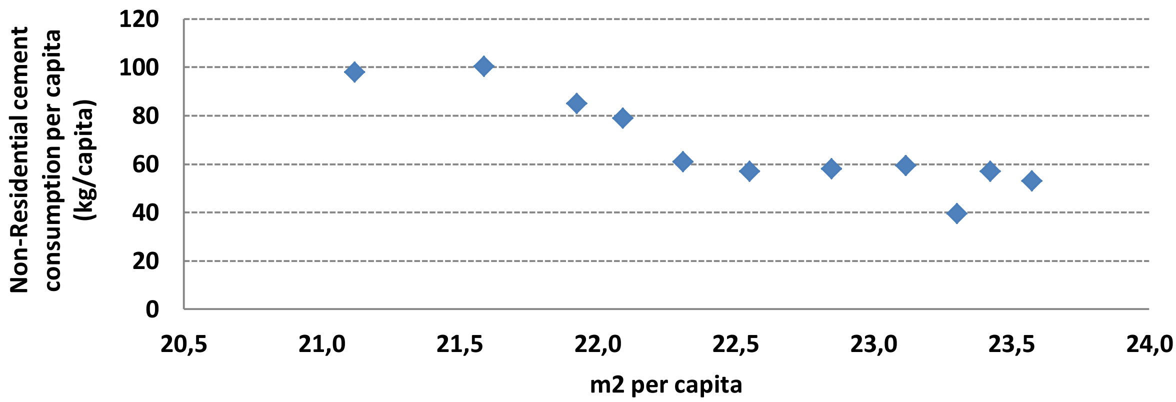

Figure 24 Non-residential cement consumption per capita and non-residential floorspace in the United States (period 1998-2008)

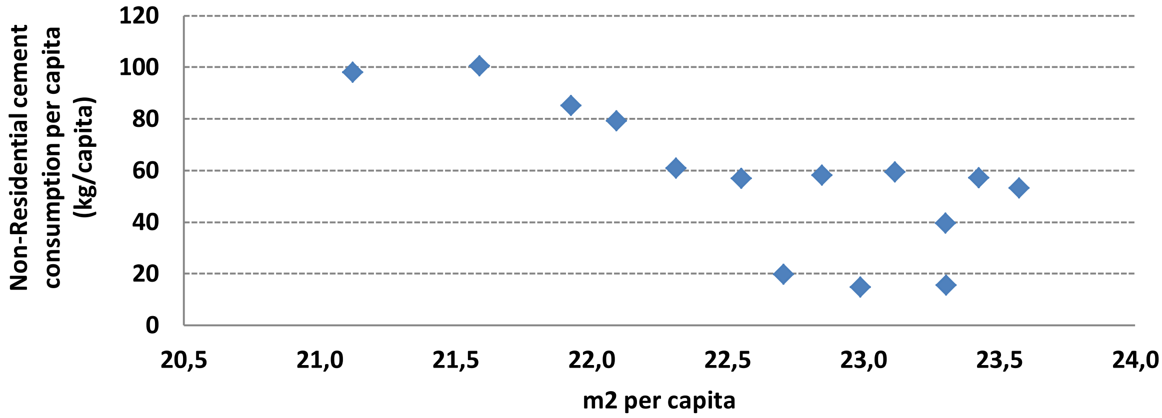

Figure 25 Non-residential cement consumption per capita and non-residential floorspace in the United States (period 1998-2011)

In the above Figures it is shown that the per capita cement consumption decreases with the increase in the non-residential floorspace. Figure 26 shows the per capita cement consumption in the non-residential sector plotted against the per capita service sector's value added. Although the value added in the service sector increases, the cement use for the construction of non-residential building decreases. The observed trends can be the result of improved material efficiency in combination with an increase in the different materials used in construction such as steel and glass. The decoupling seen in Figure 25 after 2008 could be the result of a decrease in the commissioning of new material intensive projects in combination with the completion of older projects.

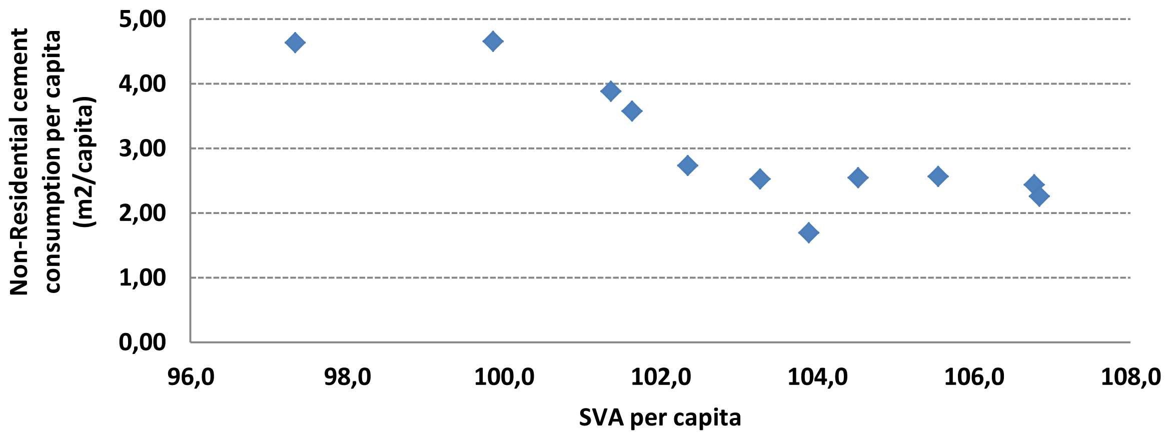

Figure 26 Per capita cement consumption in the non-residential sector and the per capita service sector's value added in the United States (period 1998 to 2008)

Figure 27 shows the correlation between the cement consumption per capita for road construction and the passenger kilometer developments in the United States for the years for which data is available. Figure 28 shows the same correlation while also including the years during the financial crisis. It can be seen that the per capita cement consumption shows an initial increase and after a plateau it decreases. The cement consumption for road/highway construction in the U.S. ranges between 120 and 140 kg/capita. The big reduction in cement use during the crisis could be attributed to the completion of older projects and the fewer projects being commissioned.

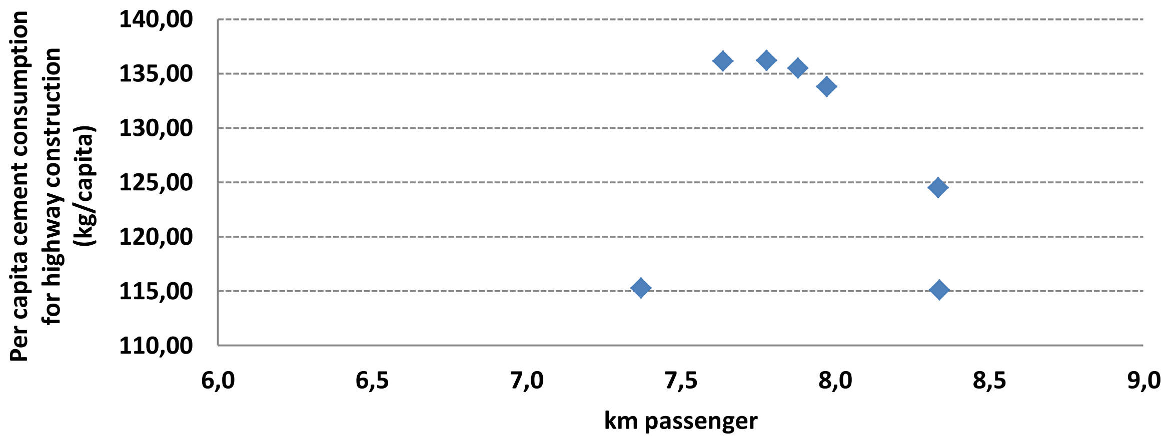

Figure 27 Per capita cement consumption for road/highway construction and km passenger in the United States (1999-2003 and 2007-2008)

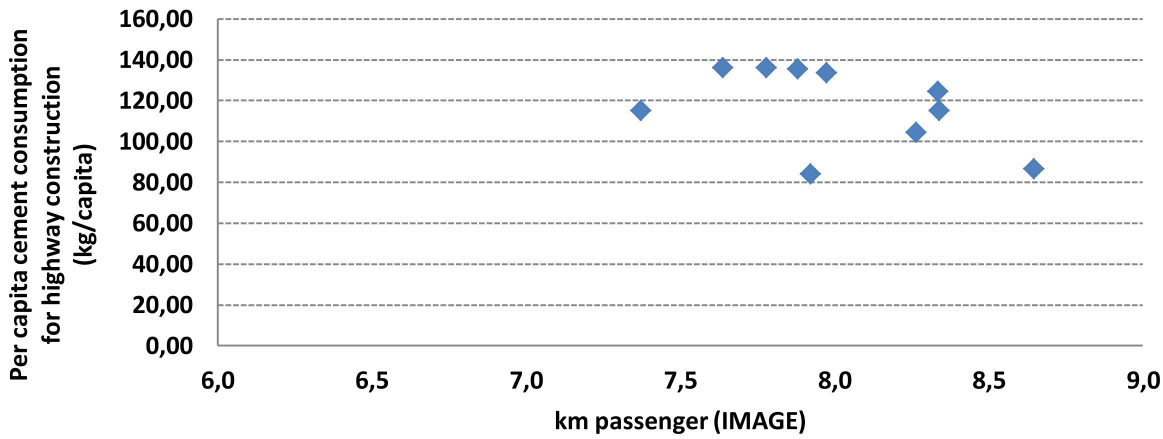

Figure 28 Per capita cement consumption for road/highway construction and km passenger in the United States (1999-2003 and 2007-2011)

The observed relationship between cement consumption in the various construction sectors and the increase in the floor space or the passenger-km could be used to forecast cement demand. However, the lack of data has complicated finding robust results.

1.1.2 Cement consumption and GDP

The inverted U-shaped curve, that describes the correlation between GDP per capita and material intensity most commonly used in models to forecast the demand for materials, has been widely used to forecast cement consumption. In general, cement demand follows the growth in income per capita. For countries moving towards industrialization cement intensity (t/$) increases following the increase in investments in construction. At a certain income per capita, cement intensity reaches a maximum and then follows a decreasing trend.

Figure 29 shows the historical development of cement production per GDP and GDP per capita for all world regions.

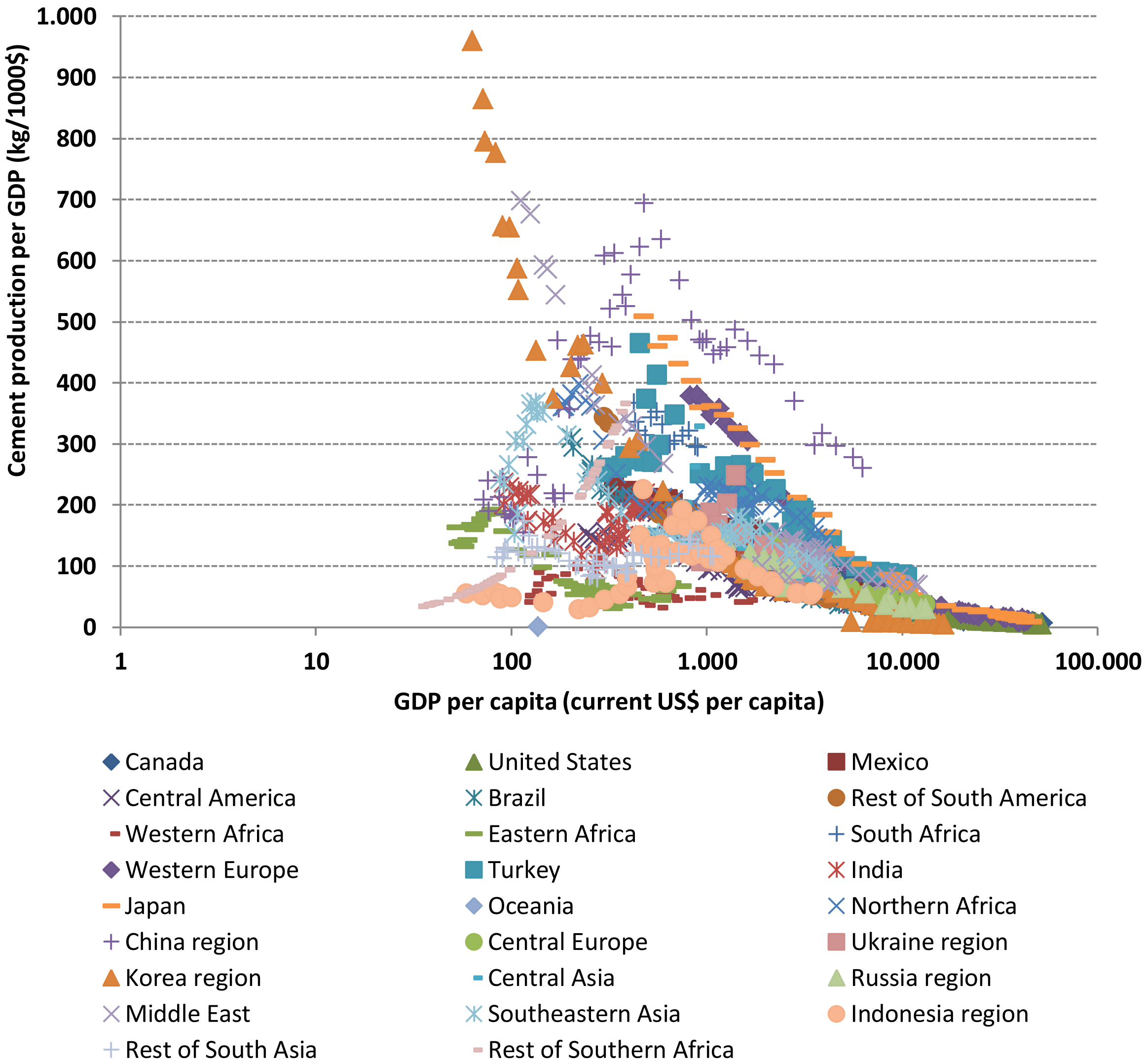

Figure 29 Per GDP production of cement versus the GDP per capita in the various world regions

Bas van Ruijven (NCAR) performed a regression analysis on the relation between per capita consumption of cement and GDP per capita. The analysis was done for the revision of the paper on heavy industry modeling in IMAGE (van Ruijven, van Vuuren et al. in prep). For this analysis, we collected data on production and trade for the period 1970-2010 for cement and 1970-2012 for steel. Detailed references for data prior to 2003 can be found in Neelis and Patel (2006) and Roorda (2006), recent steel data are obtained from the World Steel Association (2013) and cement data are from the United Nations Statistics Division (2013). We derived apparent consumption data from production and net trade. Data on GDP per capita were taken from World Bank (2014).

We evaluated multiple 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 (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.

Next to these linear models, we analyzed a non-linear model (NLI) with an S-shaped relation between GDP per capita and material consumption (also discussed in detail in 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): $C = a*e^{(B/GDP)}$
- Non-linear inverse with time-efficiency-factor (NLIT): $C= a*e^{(B/GDP)} * (1-m)^{(T - 2010)}$
- Log-inverse with time-efficiency-factor (LIT): Ln C = a + b/GDP + ln(T-1969)

We performed regression analysis for cement for all models at the global level, aggregating data to 26 regions as defined for the IMAGE model (Stehfest, van Vuuren et al. 2014). Table 2 reports 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 R^2 values for the linear models are not all comparable, since some are for absolute consumption levels and others for the ln(C). The nonlinear models stand out with the best fit to historic data (in terms of the RMSE for per capita consumption). The NLI and NLIT models are very comparable, especially since the value of the time-related efficiency improvement in NLIT is zero.

Table 6 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. AIC is the Akaike Information Criterion (see text)

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

Based on this analysis, we use the values for cement consumption from the global NLI model and assume that all regions converge towards the globally derived consumption curve by 2060 (Figure 13). 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 (Figure 13). We use a Gompertz curve to smooth out deviations between historic data and the PCC curve.

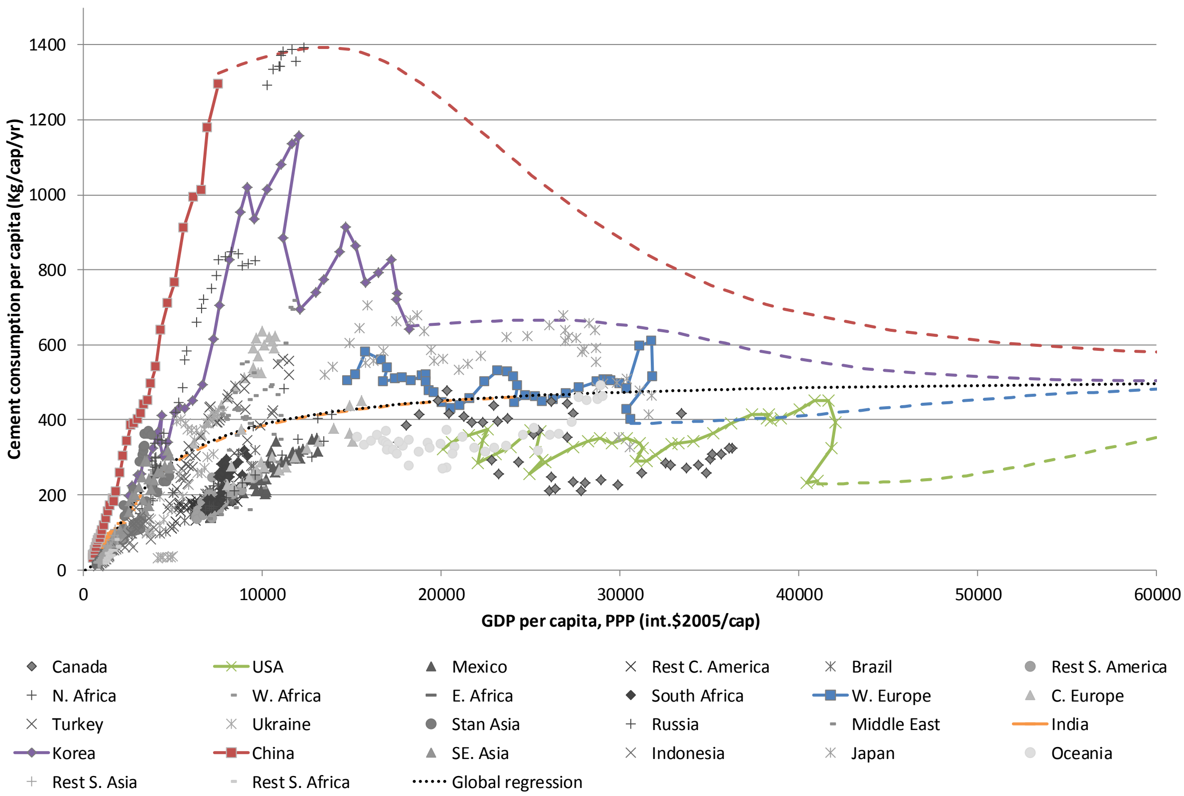

Figure 30: Per capita consumption of cement vs. GDP per capita. Historical data shown for 26 world regions for the period 1970-2010. Five major regions are highlighted: USA, Western Europe, Korea, India and China, each with future projections of per capita cement consumption in dotted lines. The black dotted line represents the global regression.

In the above paragraphs it was shown that there is a correlation between cement consumption in the different construction sectors (residential, non-residential and infrastructure) and floorspace or km passenger (Figure 22, Figure 24 and Figure 27). However, there is a big lack of time series data on the cement use per construction activity for most of the countries. The limited data availability poses a big obstacle in estimating a correlation function that can describe in a useful way the correlation between cement use and construction for all regions. Great value would be added if time series data for China (largest cement consumer) and Europe (higher concrete use in construction than the U.S.) were available for the years prior to the financial crisis.

On the other hand, modelling cement production directly with GDP, has the main advantage that there is plenty of data available.

1.1.3 Cement trade

In 2011, total international cement trade (imports plus exports) accounted for around 7.7% of total cement production (CEMBUREAU, 2013). Imports were significant in Oceania with 6.8 Mtonnes being imported to cover 41% of cement demand. In 2010, cement imports in Australia were lower (3.1 Mtonnes were imported in 2010) and covered 27% of cement demand. In Europe, about 74 Mtonnes of cement were traded (48 Mtonnes were exported and 26 Mtonnes were imported). For more details on cement imports and exports see Table 22 in the Appendix.

In general, cement trade is limited as cement is a product that is costly to transport over land. For the most common cement types, the inland transport radius is not more than 300 km. Cement however, can be transferred economically over large distances by sea (Harder, unknown date). Figure 31 shows the total cement production and consumption volumes in the various world regions.

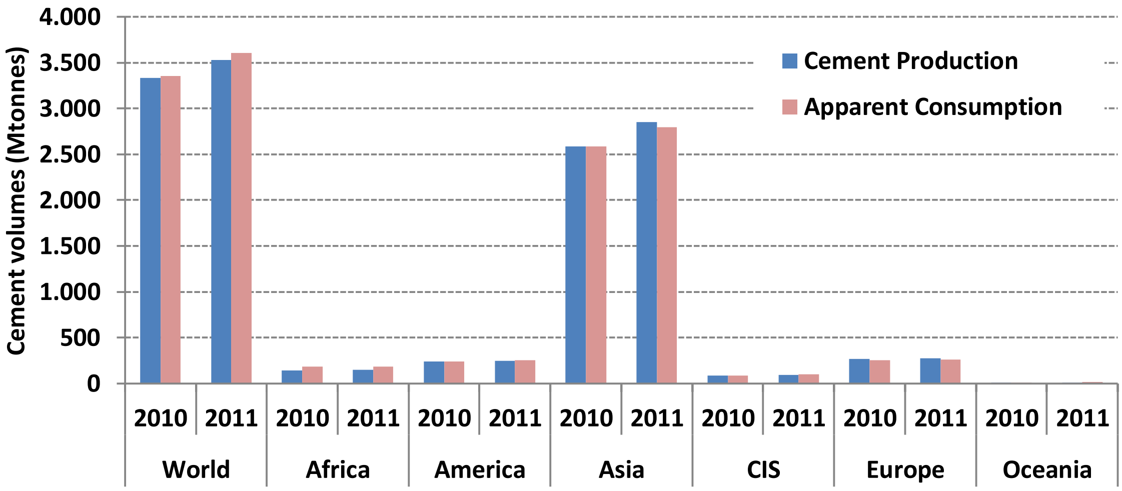

Figure 31 Cement consumption and production in 2010 and 2011 in the different world regions (based on CEMBUREAU, 2013)

As for most regions cement production is broadly equal to cement consumption, models could assume that the total cement demand of the country/region will be satisfied by the local cement production. Another simplified approach could also be to keep the historical export and import ratios constant over time.

3.2. Baseline energy use

There are three main energy consuming processes in cement manufacturing: raw material preparation, clinker production (limestone calcination) and cement grinding. Energy is consumed throughout cement manufacture and can be broken down into: (i) electricity use for raw material preparation; ii) fuel and electricity use in clinker calcination; (iii) electricity use for clinker grinding; and (iv) fuel use for drying additives (e.g. slag powder). The most energy intensive step is the calcination of clinker, responsible for the majority of the fuel use (Worrell and Galitsky, 2008).

$$E_{total,t} = E_{raw\ material\ pre.,t} + E_{fuel,kiln,t} + E_{el.,kiln,t} + E_{cement\ grinding,t} + E_{additives\ drying,t} \quad (3)$$

Table 7 Variable definitions

Variable	Definition	Unit
i	i=1, 2 refers to the type of kilns used: 1) dry and 2) wet	None
j	j refers to the different types of fuels used	None
$Kiln_{ratio,i,t}$	The share of clinker produced with clinker type i in year t	%
$SEC_{thermal,i,t}$	Thermal energy use of kiln type i in year t	GJ/tonne clinker
$SEC_{elec,i,t}$	Electricity use of kiln type i in year t. It includes the	GJ/tonne clinker

	electricity use for fuel preparation, and the electricity for operating the kiln, fans and coolers	
$SEC_{total\ el.,t}$	Electricity use for cement making in year t	GJ/tonne cement
$E_{total,t}$	Total energy use in cement manufacture in year t	PJ
$E_{cement\ grinding,t}$	Total electricity use for cement grinding in year t	PJ
$E_{raw\ material\ prep.,t}$	Total electricity use for raw material preparation in year t	PJ
$E_{additives\ drying,t}$	Total energy use for additives drying in year t	PJ
$E_{fuel,kiln,t}$	Total fuel use in cement kilns in year t	PJ
$E_{el.,kiln,t}$	Total electricity use in cement kilns in year t	PJ
$Q_{cement,t}$	Total cement output in year t	Mtonnes cement
$Q_{clinker,t}$	Total clinker output in year t	Mtonnes clinker
$CO_{2,total,t}$	Total CO_2 emissions from cement production in year t	Mtonnes CO_2
$CO_{2\text{-}fuel,t}$	Total CO_2 emissions from fuel combustion in year t	Mtonnes CO_2
$CO_{2\text{-}process,t}$	Total CO_2 emissions inherited to the clinker calcination process in year t	Mtonnes CO_2
$CO_{2\text{-}el.,t}$	Total CO_2 emissions from electricity generation in year t	Mtonnes CO_2
$Fuel_{ratio,j,t}$	Fuel share of fuel j in year t	%
$CEF_{fuel,j}$	CO_2 emission factor of fuel j	$kgCO_2/GJ$
$SEC_{thermal,t}$	Thermal energy use for clinker calcination in year t	MJ/tonne
$CEF_{el.,t}$	CO_2 emission factor for electricity generation in year t	$kgCO_2/GJ$
$SEC_{el.,t}$	Electricity use for cement making in year t	MJ/tonne cement
$Clinker_{ratio,t}$	The clinker to cement ratio in year t	%

Energy use for clinker making

Clinker is produced by burning a mixture of mainly limestone, silicon oxides, aluminium oxides and iron oxides in a kiln. Based on the moisture content of the raw materials, clinker production can take place in a wet, dry, semi-dry or semi-wet kiln. The dry process is the most energy efficient as the evaporation needs are low. Although the majority of clinker is produced with the dry process, a large amount of clinker is still produced with the more energy intensive wet process. Figure 32 shows the shares of kiln technologies worldwide (WBCSD data)[10]. Regions with a relatively high share of the wet and the semi-wet processes are the Commonwealth of Independent States (CIS) (80%), Europe 28 (19%), Australia (8%) and the United States (7%) (see Table 8).

[10] The global coverage of the WBCSD database is limited to 34% of cement production. For some regions the coverage is high (i.e. Europe and North America), while for others it is very low (i.e. China). The coverage can be seen in the Appendix in Figure 41.

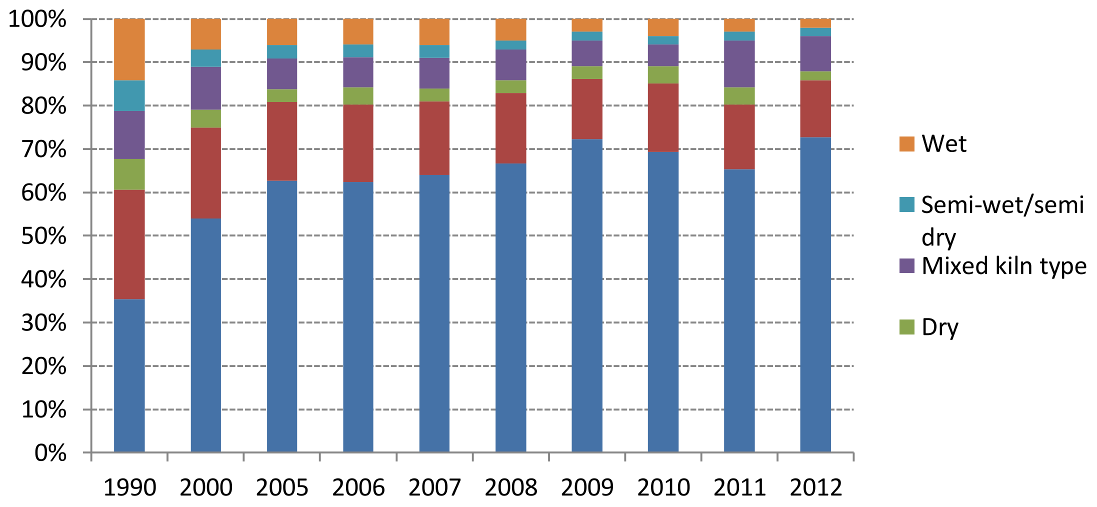

Figure 32 Global shares of clinker production produced with varying kiln types (WBCSD, 2014)

Table 8 Kiln technologies used in the different regions

	2011 Cement Production (ktonnes)[1]	Global share	Dry-process (% of clinker production)	Wet-process (% of clinker production)	Sources
Europe 28			81%	19%	WBCSD, 2014
United States	68,639	1.9%	93%	7%	USGS, 2013
Canada	12,001	0.3%	100%	0%	CIEEDAC, 2013
China	2,099,000	58.1%	89%	11%	Zhang et al., unknown date
India	240,000	6.6%	99%	1%	CSI, 2013
Russia	55,600	1.5%	13%	87%	European Union, 2009
Australia	9,100	0.3%	92%	8 %	CIF, 2014
CIS			20%	80%	WBCSD, 2009
Japan	51,291	1.4%	95%	5%	WBCSD, 2009
New Zealand	1,100	0.0%	95%	5%	WBCSD, 2009
Asia			95%	5%	WBCSD, 2009
Brazil	64,093	1.8%	100%	0%	WBCSD, 2014
Latin America			95%	5%	WBCSD, 2009
World	3,610,000				

[1] The clinker production can be estimated based on clinker to cement ratio shares for the specific regions (see Figure 38)

Countries with a high share of the wet process will have a higher average fuel use in clinker making. Table 9 shows the typical energy intensities of the different kiln technologies.

Table 9 Fuel use by type of kiln technology

Kiln technology	JRC-IPTS, 2010 (MJ/tonne clinker)	U.S. EPA, 2007 (MJ/tonne clinker)	Weighted average (MJ/tonne clinker) (WBCSD, 2009)
Dry with preheater and precalciner	3,000-4,000	2,900-3,800	3,382
Dry with preheater (without precalciner)[1]	3,100-4,200	4,419	3,699
Long dry (without preheater and precalciner)	up to 5,000	5,233	4,489
Semi-wet, semi-dry	3,300-5,400[2]	-	3,844
Wet	5,000-6,400	5,700-10,200 (6,000 typical)	6,343

[1] The energy use differs with the number of preheater stages: 3,400-3,800 MJ/tonne for 3 preheater stages; 3,200-3,600 MJ/tonne for 4 preheater stages; 3,100-3,500 MJ/tonne for 5 preheater stages; 3,000-3,400 for 6 preheater stages (ECRA, 2009)

[2] The energy use for raw material drying is not included

As a result of the kiln technology type used and the level of energy efficiency, the energy use differs per region with the thermal energy use for clinker production ranging between 3.1 and 5.0 GJ/tonne clinker (see Figure 33). The lowest energy consumption is observed in India were cement capacity increased significantly in recent years and the highest in CIS where they still rely heavily on the wet process.

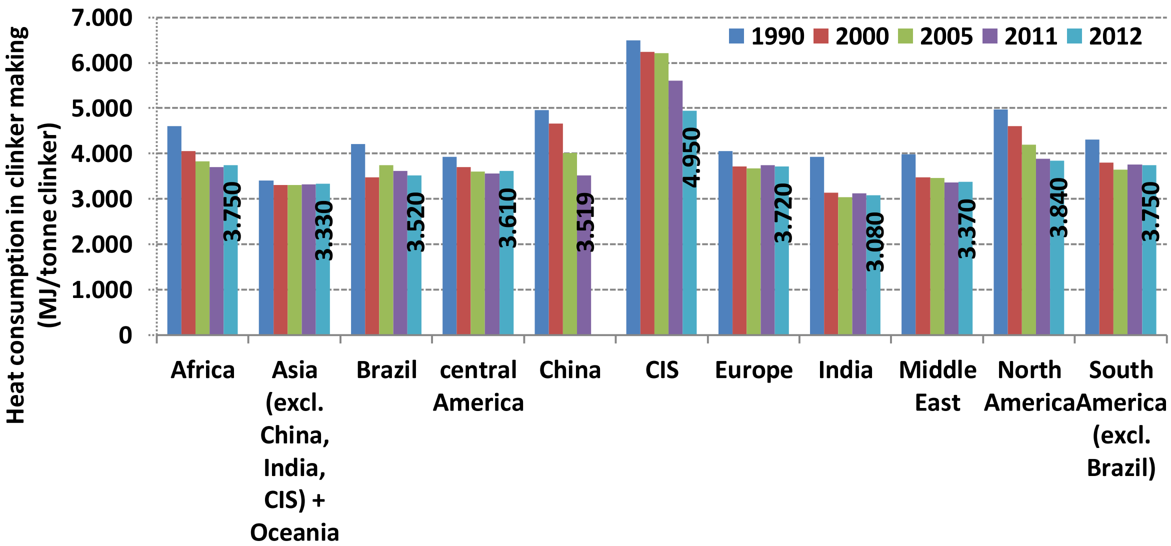

Figure 33 Heat consumption for clinker making (WBSCD, 2014; Xu et al., 2012). Heat use for raw material drying is not included

Plants using the wet process consume about 32 kWh/tonne clinker for fuel preparation and for operating the kiln, fans and the coolers while plants operating the dry process consume about 36 kWh/tonne clinker (Worrell et al., 2013).

The energy use for clinker making in a specific region can be estimated from Eq. (4) when the kiln technology breakdown and the typical fuel and electricity energy intensities are used.

$$E_{fuel,kiln,t} + E_{el.,kiln,t} = \sum_{i} Kiln_{ratio,i,t} \times SEC_{thermal,i,t} + \sum_{i} Kiln_{ratio,i,t} \times SEC_{elec,i,t} \times Q_{clinker,t}$$

(4)

Electricity use in cement plants

Most of the energy consumed in a cement plant is in the form of fuel that is used to fire the kiln. Total electricity use (electricity use for raw material preparation, kiln operation, cement and additives grinding) accounts for about 20% of the overall energy needs in a cement plant and ranges between 90 and 150 kWh/tonne cement (IPTS/EC, 2010). Electricity is primarily used for raw material, fuel and cement grinding. The typical power consumption breakdown in a cement plant using the dry process is as follows (ECRA, 2009):

- 5% raw material extraction and blending,
- 24% raw material grinding,
- 6% raw material homogenization,
- 22% clinker production and fuel grinding,
- 38% cement grinding, and
- 5% conveying, packaging and loading.

More than 60% of the electricity consumed is used for grinding. The type of the grinding technology used plays a significant role in the plants overall electricity use. Plants employing high pressure roller presses and roller mills are less electricity intensive than plants using ball mills. Table 10 and Table 11 show the typical energy intensities of the various grinding technologies.

Table 10 Electricity use[1] for raw material and cement grinding (Worrell et al., 2013)

Grinding technology	Raw material grinding (kWh/tonne raw material)	Cement grinding (kWh/tonne cement)
Ball mill	19-29	32-37
Horizontal roller mill	7-8	18-21
Vertical roller mill	<10	21-23
Roller presses	15	19-21

[1] The actual electricity use will heavily depend on the material properties and required fineness

Table 11 Electricity use[1] for fuel grinding (Worrell et al., 2013)

Grinding technology	Fuel grinding (kWh/tonne coal)
Impact mill	50-66
Tube mill	28-29
Vertical roller mill	15-23

[1] The actual electricity use will heavily depend on the material properties and required fineness

Currently, about 70% of installed mills in grinding plants are ball mills. In newer plants this share is lower, estimated at 50% as more energy efficient mills types are of preference (Harder, 2010). A more detailed information on the share of the different grinding technologies per world region would allow enable the estimation of the regional electricity use by using the typical electricity intensities of each technology. However, such information is scarce. Regional information on the different level of total electricity use [also including the electricity use for kiln operation ($E_{el.,kiln}$) seen n Eq.(3)] in cement plants is provided by the WBCSD database.

Based on the WBSCD database, in 2012, the total electricity use ranged between 82 and 126 kWh/tonne cement. The lowest electricity use is observed in India (82 kWh/tonne) and the highest in the North America (126 kWh/tonne) and CIS (121 kWh/tonne) (see Figure 34).

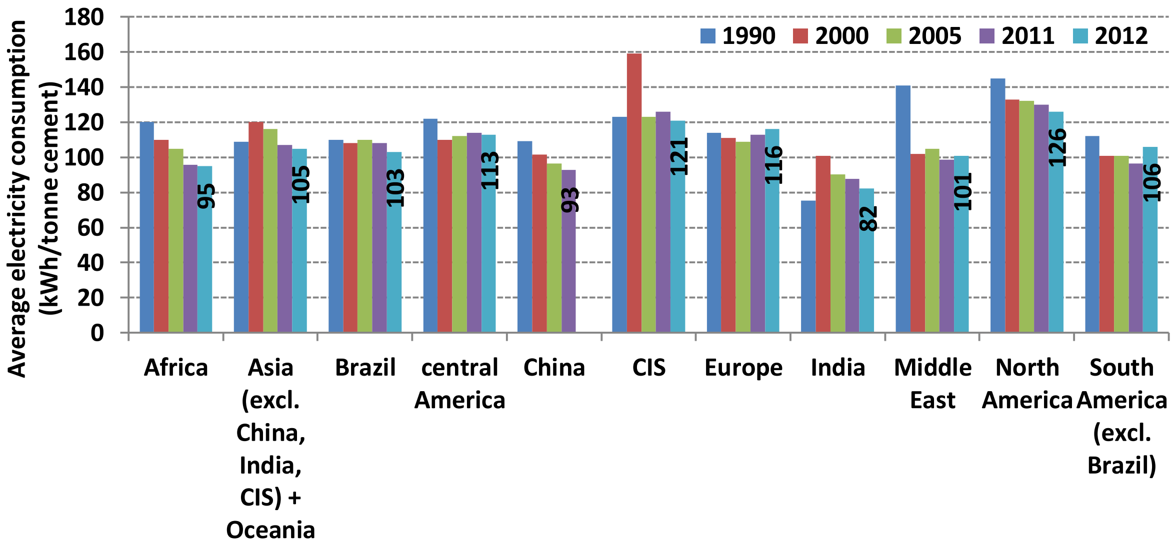

Figure 34 Average electricity consumption for cement making by geographic region (WBCSD, 2014; Xu et al., 2012)

The total energy consumption of cement making in the different world regions can thus be estimated by Eq. (5). As the available data on the electricity use from the WBCSD involve the total electricity use, in this equation, $E_{raw\ material\ prep.,t}$, $E_{el.,kiln,t}$, and $E_{cement\ grinding,t}$, from Eq. (3) is aggregated into $SEC_{total\ el.,t}$.

$$E_{cement,t} = \sum_{i} Kiln_{ratio,i,t} \times SEC_{thermal,i,t} \times Q_{clinker,t} + SEC_{total\ el.,t} \times Q_{cement,t}$$

(5)

A simple way to determine the energy use under a baseline scenario would be to assume that the energy efficiency in cement manufacture improves annually by a certain rate. This improvement on the energy efficiency would be the result of an autonomous energy efficiency improvement and a policy induced energy efficiency improvement.

The autonomous energy efficiency improvement occurs due to technological developments. Each new generation of capital goods is likely to be more energy efficient than the previous one. Energy efficiency improvements also occur due to the various policy measures where actors change their behavior, and invest for example into technologies characterized by improved energy efficiencies. In this analysis, both the autonomous and the policy-induced energy efficiency improvements fall under the same definition of energy efficiency improvements.

The historical energy use trends for the cement industry indicate that in the past years, the fuel use in clinker production and the electricity use for cement production (total electricity use) experienced an annual decrease of 0.9% and 0.5%, respectively (Kermeli et al., 2014). These two rates could thus be used to determine the energy use under a baseline scenario.

3.3. Energy efficiency improvements

A wide variety of measures have been identified able to reduce the energy use and CO_2 emissions in the different process steps in cement manufacture.

Table 12 and Table 13 list energy efficiency improvement measures for cement plants operating the dry process, and Table 14 and Table 15 for cement plants operating the wet process.

Table 12 Energy efficiency measures for clinker making – dry process cement plants (Worrell et al., 2013)

Energy Efficiency Measure	Specific Fuel Savings (GJ/tonne clinker)[1]	Specific Electricity Savings (kWh/tonne clinker)[1]	Investment Cost ($/tonne clinker)[1]	Estimated Payback Period (years)[1]
Raw Materials Preparation				
Mechanical Transport Systems	-	1.2 - 3.5	0.2-5.2	>3 (1)
Improved Pneumatic Systems	-	1.9	N/A	N/A (1)
Improved Raw Mill Blending	0.0-0.02	1.3-4.2	3.5-6.3	>10 (1)
Use of Vertical Roller Mills	-	10.9-12.9	8.0-36.0	>10 (1)
Use of High-Pressure Roller Presses	-	20.0-20.8	7.60	7.0-8.0 (1)
High Efficiency Classifiers	-	4.6-6.3	3.10	>10 (1)
Separate Raw Material Grinding	-	1.0-1.4	5.8-23	>10 (1)
Raw Meal Process Control	-	1.5-1.8	N/A	1
Fuel Preparation	-	0.8-2.4	N/A	N/A (1)
Clinker Making				
Energy Management and Control Systems	0.1-0.2	0-4.9	0.2-0.3	<2
Kiln Combustion System Improvements	0.1-0.4	-	1.00	1.0-5.0 (1)
Mineralized Clinker	0.0-0.2	0- -1.0	N/A	N/A
Indirect Firing	0.2	0- -0.6	6.7-9.3	>10 (1)
Oxygen Enrichment	0.0-0.2	(-)9- (-)32	3.5-6.9	N/A(1)
Mixing Air Technology (PH kilns)	0.20	(-) 0.03	1.2	2 (1)
Seal Replacement	0.02	-		<1
Kiln Shell Heat Loss Reduction	0.1-0.6	-	0.3	<1
Preheater Shell Heat Loss Reduction	0.02	-	0.3	6

Refractories	0.06	-	0.7	4
Conversion to Grate Cooler	0.3	(-)3.00- (-)6.00	10-14	>18
Optimize Grate Cooler	0.05-0.16	0.0- (-)2.0	0.7-2.1	2.00-7.00
Low-Pressure Drop Suspension Preheaters	-	0.6-4.4	3-4	>10 (1)
Heat Recovery for Power Generation	-	20.0	2.2-10.4	2.00-14.00 (1)
Conversion of Long Dry to Preheater	0.7-1.6	-	40.0	10 (1)
Increase Preheater Stages (from 5 to6)	0.1	-	2-5	>7 (1)
Addition of Precalciner or Upgrade	0.2-0.7	-	15.0	>10 (1)
Conversion of Long Dry Kiln to Preheater Precalciner	0.84-1.11	-	30.0	>10 (1)

[1] The estimated energy and expenditure savings and payback periods are averages for indication, based on the average performance of the U.S. cement industry (e.g. clinker to cement ratio). The actual savings and payback period may vary by project based on the specific conditions in the individual plant.

Table 13 Energy efficiency measures for cement making – dry process cement plants (Worrell et al., 2013)

Energy Efficiency Measure	Specific Fuel Savings (GJ/tonne cement)	Specific Electricity Savings (kWh/tonne cement)	Investment Cost ($/tonne cement)	Estimated Payback Period (years)[1]
Finish Grinding				
Energy Management and Process Control	-	1.6-8.5		<2
Vertical Roller Mills	-	9.0-20	7-39	>8 (1)
Horizontal Roller Mills	-	15.6	16	>10 (1)
High-Pressure Roller Presses - pregrinding	-	5.00-10.00	6	>10 (1)
High-Pressure Roller Presses - finish grinding	-	11.00-25.00	16.00	>10 (1)
Improved Grinding Media	-	1.8	2.5	>10 (1)
High-Efficiency Classifiers	-	1.70-6.00	1.5-3.0	>5 (1)
Plant Wide Measures				
Preventative Maintenance	0.04	0.00-5.00	N/A	<1
High Efficiency Motors	-	0.00-5.00	N/A	<1
Adjustable Speed Drives	-	5.50-9.00	0.2-0.9	1.00-3.00
Optimization of Compressed Air Systems	-	0.00-2.00	N/A	<3
High Efficiency Fans	-	0.9	N/A	N/A

Efficient Lighting	-	0.00-0.50	N/A	N/A

[1] The estimated energy and expenditure savings and payback periods are averages for indication, based on the average performance of the U.S. cement industry (e.g. clinker to cement ratio). The actual savings and payback period may vary by project based on the specific conditions in the individual plant.

Table 14 Energy efficiency measures for clinker making – wet process cement plants (Worrell et al., 2013)

Energy Efficiency Measure	Specific Fuel Savings (GJ/tonne clinker)[1]	Specific Electricity Savings (kWh/tonne clinker)[1]	Investment Cost ($/tonne clinker)[1]	Estimated Payback Period (years)[1]
Raw Materials Preparation				
Slurry Blending and Homogenizing	-	0.1-0.8	N/A	<3
Wash Mills with Closed Circuit Classifier	-	9.2-12.9	N/A	>10 (1)
High Efficiency Classifiers	-	4.6-6.3	N/A	>10 (1)
Fuel Preparation	-	1.0-3.0	N/A	N/A (1)
Clinker Making				
Energy Management and Control Systems	0.2-0.3	0-4.9	0.2-0.3	<1
Kiln Combustion System Improvements	0.1-0.7	-	1.00	<3 (1)
Mineralized Clinker	0-0.3	0- -1.0	N/A	N/A
Indirect Firing	0.2	0- -0.6	6.7-9.3	>10 (1)
Oxygen Enrichment	0.0-0.3	(-)10- (-)35	3.5-6.9	N/A(1)
Mixing Air Technology	0.30	(-) 0.03	1.2	1 (1)
Seal Replacement	0.03	-		<1
Kiln Shell Heat Loss Reduction	0.1-0.6	-	0.25	<1
Refractories	0.06	-	0.7	4
Conversion to Grate Cooler	0.5	(-)3.00- (-)6.00	10-14	9.00-12.00
Optimize Grate Cooler	0.05-0.16	0.0- (-)2.0	0.7-2.1	2.00-7.00
Conversion to Semi-Dry Process Kiln	1.2-1.6	(-) 5.5- - 7.7	N/A	>10 (1)
Conversion to Semi-Wet Process Kiln	0.8-1.2	-4.4	1.8-4.0	1.00-3.00
Conversion to Dry precalciner Kiln	2.2-3.4	-10	55	>7 (1)

[1] The estimated energy and expenditure savings and payback periods are averages for indication, based on the average performance of the U.S. cement industry (e.g. clinker to cement ratio). The actual savings and payback period may vary by project based on the specific conditions in the individual plant.

Table 15 Energy efficiency measures for cement making – wet process cement plants (Worrell et al., 2013)

Energy Efficiency Measure	Specific Fuel Savings (GJ/tonne cement)	Specific Electricity Savings (kWh/tonne cement)	Investment Cost ($/tonne cement)	Estimated Payback Period (years)[1]
Finish Grinding				
Energy Management and Process Control	-	1.6-8.5		<2
Vertical Roller Mills	-	9.0-20	7-39	>8 (1)
Horizontal Roller Mills	-	15.6	16	>10 (1)
High-Pressure Roller Presses - pregrinding	-	5.00-10.00	6	>10 (1)
High-Pressure Roller Presses - finish grinding	-	11.00-25.00	16.00	>10 (1)
Improved Grinding Media	-	1.8	2.5	>10 (1)
High-Efficiency Classifiers	-	1.70-6.00	1.5-3.0	>5 (1)
Plant Wide Measures				
Preventative Maintenance	0.04	0.00-5.00	N/A	<1
High Efficiency Motors	-	0.00-5.00	N/A	<1
Adjustable Speed Drives	-	5.50-9.00	0.2-0.9	1.00-3.00
Optimization of Compressed Air Systems	-	0.00-5.00	N/A	<3
High Efficiency Fans	-	0.9	N/A	N/A
Efficient Lighting	-	0.00-0.50	N/A	N/A

[1] The estimated energy and expenditure savings and payback periods are averages for indication, based on the average performance of the U.S. cement industry (e.g. clinker to cement ratio). The actual savings and payback period may vary by project based on the specific conditions in the individual plant.

There are several ways with which energy efficiency improvements could be incorporated into the models. Some of them are:

- *Cost-supply curves*

Cost-supply curves are a useful tool, that is used to present the cost-effective as well as the technical energy and GHG savings potentials of several energy efficiency measures. To construct the curves, the energy and GHG emission mitigating measures/technologies are ranked based on their Cost of Conserved Energy (CCE), or Cost of Mitigated Greenhouse Gases ($C_{CO2\text{-}eq}$). The cost-supply curves show in the y-axis the CCE or the $C_{CO2\text{-}eq}$ and in the x-axis the cumulative energy savings and the cumulative GHG emission savings. The width of each segment in the graph shows the energy or GHG savings potential of each energy efficiency improvement measure.

The CCE and the $C_{CO2\text{-}eq}$ can be determined with the use of Eq.7 and Eq.8, respectively.

$$CCE = \frac{Annualized\ investment\ cost + Annual\ O\&M\ costs - Annual\ Financial\ benefits\ from\ energy\ savings}{Annual\ energy\ savings}$$

(7)

$$C_{CO2} = \frac{Annualized\ investment\ cost + Annual\ O\&M\ costs - Annual\ Financial\ benefits\ from\ energy\ savings}{Annual\ GHG\ emission\ savings}$$

(8)

The annualized investment cost is a function of the discount rate and the technical lifetime of the technology and can be calculated from Eq.9.

$$Annualized\ investment\ cost = Investment\ cost \times \frac{d}{(1 - (1 + d)^{-n})}$$

(9)

Where *d* is the discount rate and *n* the technical lifetime of the measure.

With the use of different energy prices for each country/region some measures that are found to be cost-effective in one country/region might not be cost-effective in another. With the use of cost-supply curves, an increase in energy prices due to for example policy measures, will for some measures result in switching from non-cost-effective to cost-effective. In addition, the energy prices for which important energy efficiency measures (measures with high energy savings can be determined) become cost-effective can be determined.

- *Payback period*

The payback period (PBP) could be estimated for every measure (see Eq. 10). All measures can then be ranked based on their PBP. The measures with the lowest PBP will be implemented first.

$$PBP = \frac{Initial\ investment}{Annual\ opreational\ benefits - Annual\ operational\ costs}$$

(10)

- *Step functions*

The wide range of energy efficiency measures could also be clustered based on the required investments costs into a) low investment measures, b) medium investment measures, and c) high investment measures. The model can then use a step function (Figure 35) and assess how much the energy consumption can decrease and at what cost.

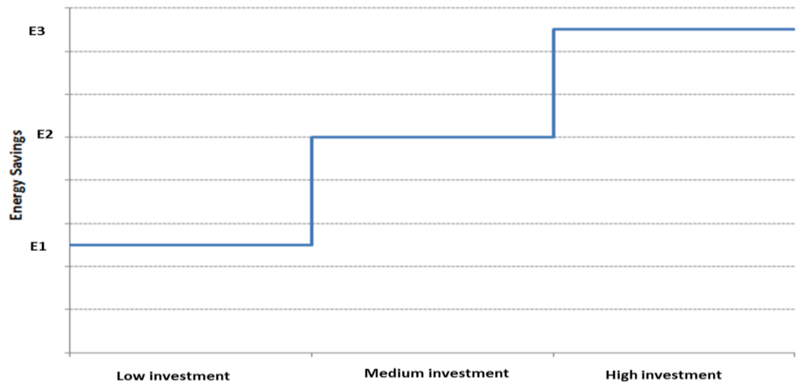

Figure 35 Energy saving potentials based on the investment cost

In addition, the measures could be clustered in the measures that could decrease the energy use in clinker production (measures that improve the energy efficiency in raw material preparation and clinker burning) and in cement production (measures that improve the energy efficiency in finish grinding). Table 16 and

Table 17 show the aggregated based on the investment costs energy efficiency improvement opportunities. Low investment measures are measures that will typically have a PBP of less than 3 years, medium investment measures are measures with a PBP of 3-5 years and high investment measures are measures with a PBP higher than 5 years.

Table 16 Energy efficiency improvements in clinker making clustered based on the investment costs (dry process)

Energy Efficiency Measures	Specific Fuel Savings (GJ/tonne clinker)	Specific Electricity Savings (kWh/tonne clinker)	Investment Cost ($/tonne clinker)
Low Investment Measures	0.4-1	1.5-6.7	1.7-1.8
Medium Investment Measures	0.2-0.6	-0.8-3.5	2.9-9.3
High Investment Measures	1.3-1.6	41-54	72-108

Table 17 Energy efficiency improvements in cement making clustered based on the investment costs (dry process)

Energy Efficiency Measure	Specific Fuel Savings (GJ/tonne cement)	Specific Electricity Savings (kWh/tonne cement)	Investment Cost ($/tonne cement)
Low Investment Measures	0.04	8-31	1.40
Medium Investment Measures	-	1.7-6	1.5-3
High Investment Measures	-	18-37	~25

Detailed information on the current level of penetration of the different technologies on a country level is not available (except for the information available on the type of cement kilns "wet" or "dry" used, see Table 8). The implementation rates of the energy efficiency improving measures will vary per region depending on the current level of energy efficiency and can be estimated based on the technical energy savings potentials from the wide implementation of Best Available Technologies (BATs).

Dry kilns equipped with a precalciner and several preheater stages (5 to 6), are currently considered best available technology, and can have under optimal conditions a fuel consumption of about 2.9-3.3 GJ/tonne clinker (IPTS/EC, 2010). Concerning raw material and finish grinding, current state-of-the-art techniques use roller presses and vertical roller mills. The electricity requirements will mainly depend on raw material hardness, moisture content and the type and amount of additives used. Best practice electricity use for cement making is based on Worrell et al. (2008) for cement with 65% Blast Furnace Slag (BFS). Figure 36 shows the technical fuel and electricity savings potentials from BAT implementation.

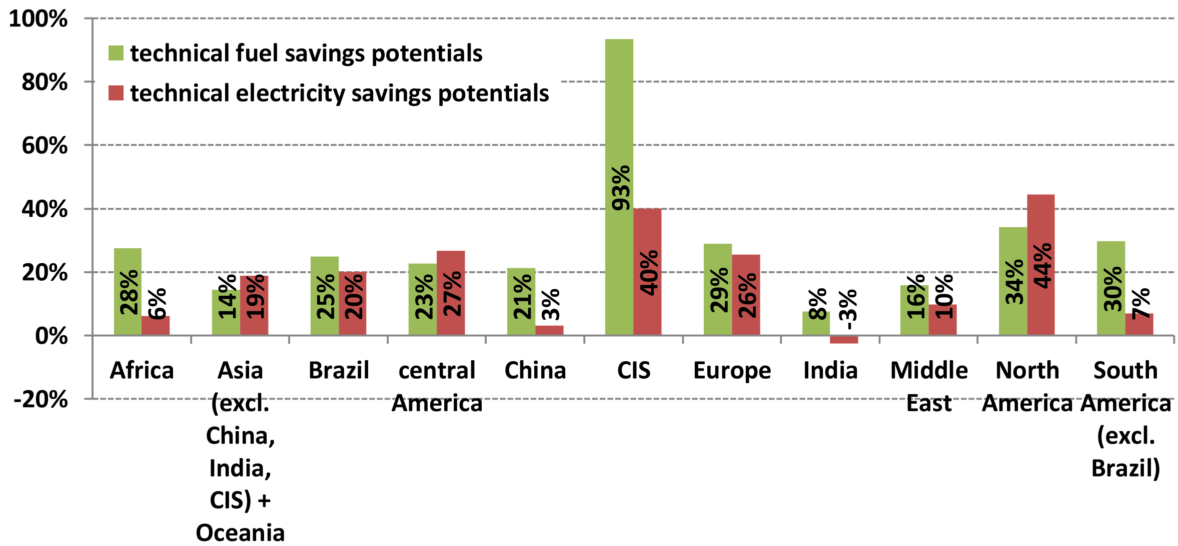

Figure 36 Estimated technical energy savings potentials from wide BAT adoption

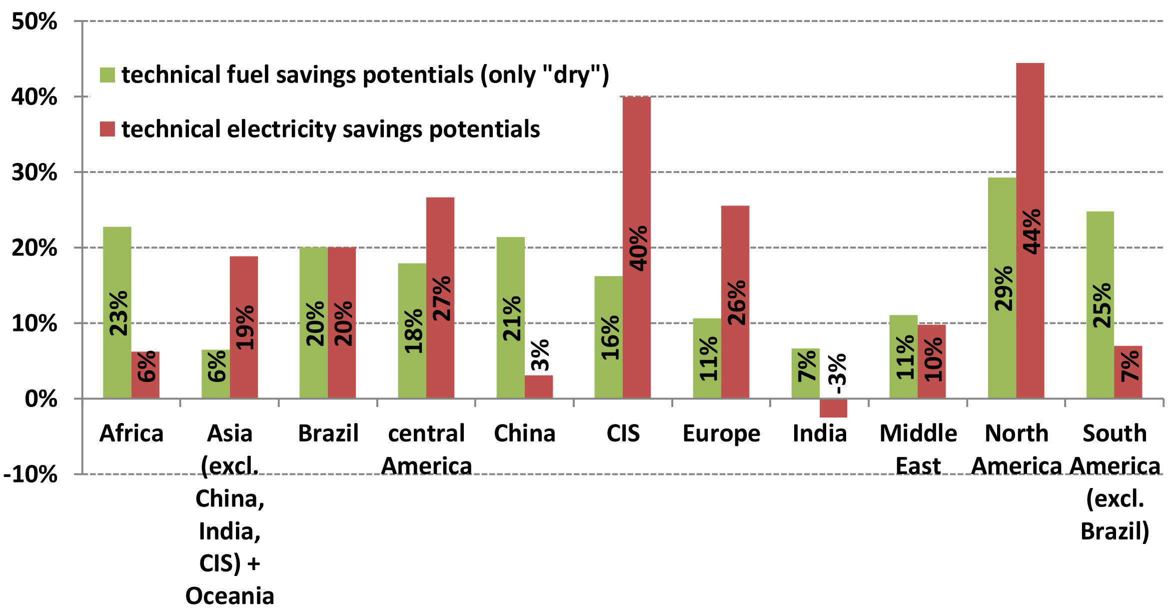

Figure 37 Estimated technical energy savings potentials from wide BAT adoption (dry process plants)

Figure 37 shows the estimated technical fuel and electricity savings potentials for dry plants. To estimate these potentials we considered that all wet plants dropped to BAT levels by adopting state-of-the-art dry cement kilns with preheaters and precalciners[11].

3.4. Baseline CO_2 emissions

Most of the CO_2 emissions in cement making are released during clinker calcination. Approximately 62% of the CO_2 emissions are process related while the remaining 38% is released during fuel combustion (IPTS/EC, 2010). The CO_2 emissions inherent to the process amount to 0.5262 kg per kg of clinker produced (IPTS/EC, 2010). The CO_2 emissions from fuel combustion depend on the energy intensity of the kiln system and the carbon intensity of the fuel used. To calculate the total amount of CO_2 released in the atmosphere, the CO_2 emissions from electricity generation also need to be added.

$$CO_{2,total,t} = CO_{2-fuel,t} + CO_{2-process,t} + CO_{2-el.,t}$$
$$= \sum_j (Fuel_{ratio,j,t} \times CEF_{fuel,j} \times SEC_{thermal,t}) \times Q_{cement,t} + \sum_i (CEF_{el.,t} \times$$
$$\times SEC_{el.,t}) \times Q_{cement,t} + 0.5262 \times Clinker_{ratio,t} \times Q_{cement,t} \quad (6)$$

Data on linker production is not reported on a country or a regional level. However, clinker production can be estimated by multiplying the reported cement production with the regional clinker to cement ratios seen in Figure 38. Clinker can be substituted by industrial by-products such as coal fly ash, blast furnace slag or pozzolanic materials (e.g. volcanic material). The relative importance of additive use can be expressed by the clinker to cement ratio.

[11]For the estimation we considered that the energy use in wet plants was reduced by 2,800 MJ/tonne clinker (that is 5,700 MJ/tonne for the typical fuel use in wet plants minus 2,900 MJ/tonne in state-of-the-art dry plants). The share of the clinker produced with the wet process can be found in Table 8. Due to the lack of information, it was assumed that the share of wet plants on the overall clinker production in Africa, Central America, Brazil and Middle East is low, equal to 5%.

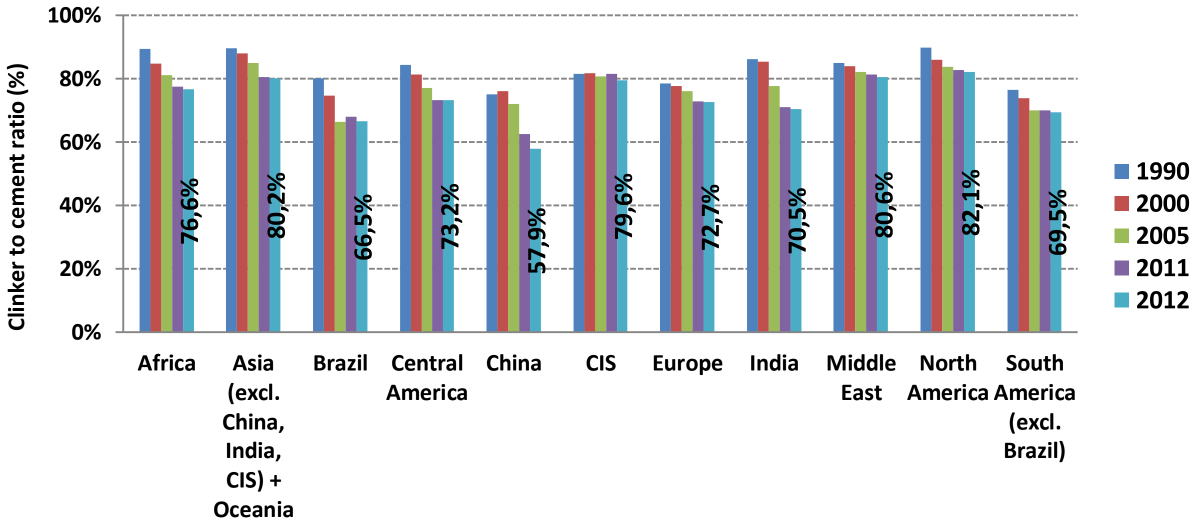

Figure 38 Clinker to cement ratios in the various world regions (WBCSD, 2014; Xu et al., 2012; Zhang et al., unknown date)

Figure 39 shows the different types of fuels used in the cement industry. In Europe, around 45% is comprised by alternative fuels such as waste and biomass.

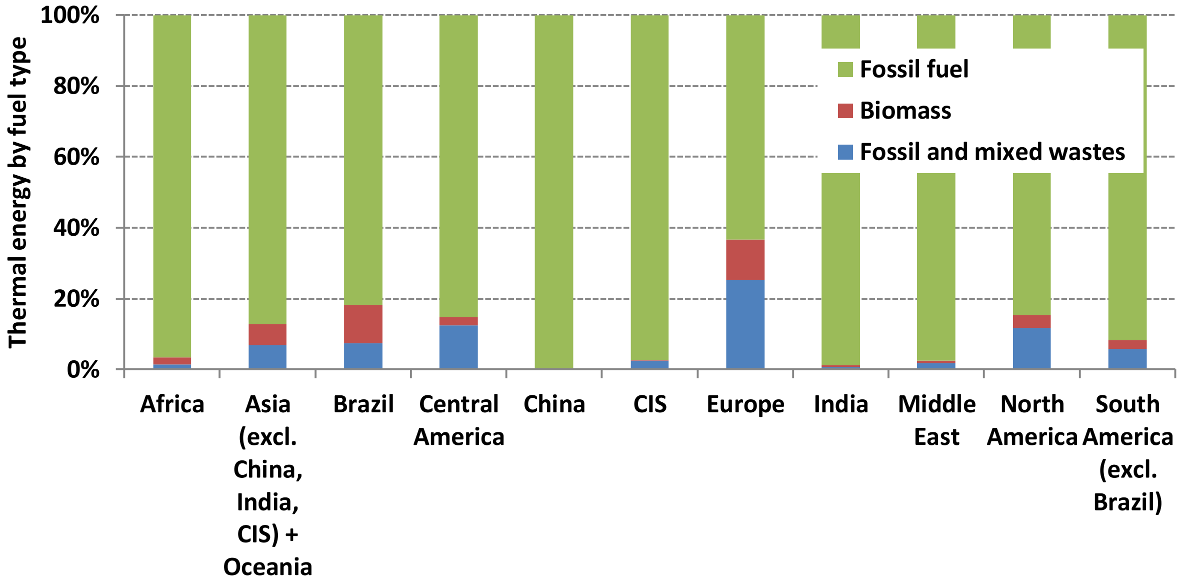

Figure 39 Thermal energy use for clinker making by fuel type (WBCSD, 2014)

3.5. Clinker substitution

Clinker production is the most energy intensive step in cement manufacture. Moreover, clinker making accounts for about two thirds of CO_2 emissions. The adoption of measures that can reduce the clinker content in cement will not only improve the energy efficiency and limit the CO_2 emissions from fuel combustion but also reduce the process CO_2 emissions. Reducing the clinker to cement ratio is considered the most effective way of reducing CO_2 emissions and increasing energy efficiency (Huntzinger and Eatmon, 2009).

The type of cement most widely used is Portland cement and has a clinker content of 95%. Other cement types use a variety of clinker substitutes such as fly ash, pozzolans, granulated blast furnace slag, silica fume, and volcanic ash in various proportions. These substitutes have similar properties to cement and can either be used in the kiln feed (feedstock change) or substitute clinker in the cement or the concrete mix (product change). Table 18 shows the composition of different cement types and the maximum amount of additives that can be used.

Table 18 Typical composition of different cement types (IPTS/EC, 2010)

<table>
<tr><th></th><th>Portland cement</th><th>Portland-composite cements</th><th>Blast furnace cement</th><th>Pozzolanic cement</th><th>Composite cement</th></tr>
<tr><td>Clinker</td><td>95-100%</td><td>65-94%</td><td>5-64%</td><td>45-89%</td><td>20-64%</td></tr>
<tr><td>Blast furnace slag</td><td>-</td><td rowspan="3">6-35%</td><td>36-95%</td><td>-</td><td>18-50%</td></tr>
<tr><td>Fly ash</td><td>-</td><td>-</td><td rowspan="3">11-55%</td><td rowspan="2">18-50%</td></tr>
<tr><td>Pozzolana</td><td>-</td><td>-</td></tr>
<tr><td>Silica fume</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Other additives (e.g. gypsum)</td><td>0-5%</td><td>0-5%</td><td>0-5%</td><td>0-5%</td><td>0-5%</td></tr>
</table>

The production of blended cements involves the intergrinding of clinker with one or more additives. The intergrinding of one tonne of additives will offset the environmental impact (NOx, SO_2, CO_2, PM and other emissions) of producing one tonne of Portland cement (about 0.95 tonnes of clinker) (Staudt, 2009).

The use of blended cements is very common in Europe. About 12% of the cement consumed in Europe is blast furnace and pozzolanic cements, while portland composite cement accounts for an additional 59% (IPTS/EC, 2010). In Europe, a common standard has been developed for 25 types of cement (using different compositions for different applications). The European standard allows wider applications of additives when compared to other countries, such as the U.S., where the use of blended cements is limited. Figure 40 shows the share of additives use in cement manufacture in the different regions. Regions with the highest additive content in cement are Brazil (32%), South America (excl. Brazil) (29%), India (28%) and Central America (26%).

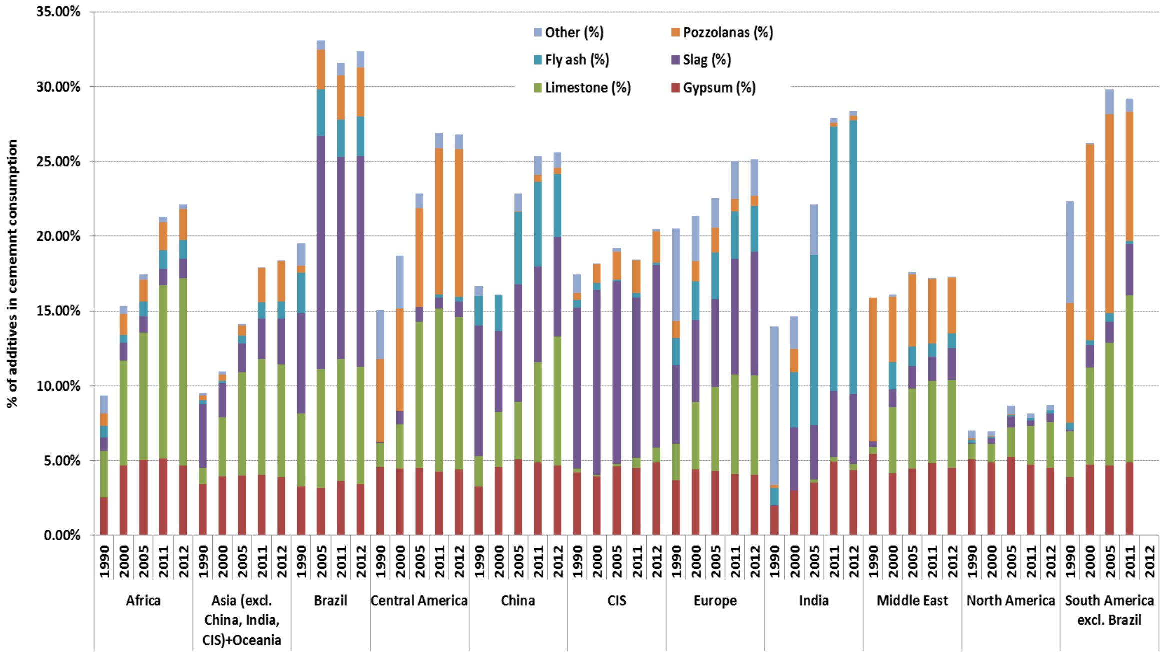

Figure 40 Weighted average of additives content in cement per region (WBCSD, 2014)

Note: According to the WBCSD (2014), in 2012, the additive content in cement in North America, was equal to 9%. However, this percentage is considerably lower than anticipated as according to the same source, the clinker to cement ratio in 2012 was 82% (see Figure 38).

Table 19 and Table 20 show the measures that could decrease the clinker to cement ratio along with the fuel savings potentials and representative for the U.S. industry. Increasing the use of clinker substitutes in cement will result in higher electricity use for cement grinding.

Table 19 Material efficiency improvements – dry process plants (based on Worrell et al., 2013)

Energy Efficiency Measure	Specific Fuel Savings (GJ/tonne cement)[1]	Specific Electricity Savings (kWh/tonne cement)[1]	Investment Cost ($/tonne cement)[1]	Estimated Payback Period (years)[1]
Product Change				
Blended Cement	1.0[2]	-15.00	0.7-5.9	0.50-3.00
Limestone Portland Cement	0.2	3.0	N/A	<1
Feedstock Change				
Use of Steel Slag in Clinker (CemStar) (10% substitution)	0.2	-	0.7-0.8	1.00-2.00
Use of Fly Ash, Blast Furnace Slag in Clinker (15% substitution)	0.3	0.00 - (-)1.70		<7.00 (1)
Use of Cement Kiln Dust in Clinker	0.1	-0.9	0.1	<2
Use of Calcareous Oil Shale in Clinker (8% oil shale)	0.1	-	0.1	10 (1)

[1] The estimated energy and expenditure savings and payback periods are averages for indication, based on the average performance of the U.S. cement industry (e.g. clinker to cement ratio). The actual savings and payback period may vary by project based on the specific conditions in the individual plant.

[2] Estimated for a 27% decrease of the clinker to cement ratio (from 89% U.S. average in 2009, to 65%). The fuel savings increase almost linearly with the increase in the BFS use. The energy savings will be equal to the fuel use for cement making in the base case (GJ/tonne cement) minus the fuel use for clinker making in the base

case (GJ/tonne clinker) multiplied by the new clinker to cement ratio (%). When BFS is used, about 0.09 GJ/tonne cement of fuel are needed for drying while 0.2 GJ/tonne are saved from bypassing (for more details see Worrell et al., 2013).

Table 20 Material efficiency improvements – wet process plants (based on Worrell et al., 2013)

Energy Efficiency Measure	Specific Fuel Savings (GJ/tonne cement)[1]	Specific Electricity Savings (kWh/tonne cement)[1]	Investment Cost ($/tonne cement)[1]	Estimated Payback Period (years)[1]
Product Change				
Blended Cement	1.60	-15.00	0.7-5.9	0.50-2.00
Limestone Portland Cement	0.30	3.00	N/A	<1
Feedstock Change				
Use of Steel Slag in Clinker (CemStar)	0.2	-	0.7-0.8	1.00-2.00
Use of Fly Ash, Blast Furnace Slag in Clinker	0.3	0.00 - (-)1.70		<7.00 (1)
Use of Calcareous Oil Shale in Clinker	0.1	-	0.1	10 (1)

[1] The estimated energy and expenditure savings and payback periods are averages for indication, based on the average performance of the U.S. cement industry (e.g. clinker to cement ratio). The actual savings and payback period may vary by project based on the specific conditions in the individual plant.

The energy savings from increasing the level of use of supplementary cementitious materials (i.e. decreasing the clinker to cement ratio) will vary per country/region as they are dependent on the current level of fuel use for clinker making and the average clinker to cement ratio. Table 21 shows the regional energy savings from decreasing the clinker to cement ratio in all regions to 65%.

Table 21 Energy savings from decreasing the clinker to cement ratio to 65%

	Energy savings (MJ/tonne cement)	
	2011	**2012**
Africa	463	435
Asia (excl. China, India, CIS) + Oceania	518	506
Brazil	109	53
central America	292	296
China	0[1]	-
CIS	931	723
Europe	292	286
India	190	169
Middle East	551	526
North America	692	657
South America (excl. Brazil)	192	169

[1] The energy savings in China are zero as the clinker to cement ratio in 2011 was 62.5% (less than 65%)

To calculate the energy savings from the adoption of lower clinker to cement ratios in each region use Eq.(11):

$$Energy\ savings = SEC_{thermal,t} \times Clinker_{ratio,t} - SEC_{thermal,t} \times Clinker_{New\ Ratio} \quad (11)$$

The development of the clinker to cement ratio in the various world regions can be very hard to forecast, as the use of supplementary cementitious materials depends on several parameters (ECRA, 2009):

- Availability of supplementary cementitious materials
- Price of clinker substitutes
- National standards
- Market acceptance
- Cement properties

Although granulated blast furnace slag, fly ash and pozzolanas are materials that are widely available, their regional availability varies widely. The availability of granulated blast furnace slag (GBFS) depends on the location and output of blast furnaces used for the production of pig iron. It is estimated that about 200 million tonnes of GBFS are produced worldwide (ECRA, 2009). About 275 kg of blast furnace slag are generated for every tonne of crude steel produced with the BF/BOF route (Worldsteel, 2014). Not all BFS is produced as granulated slag, some of the BFS is air-cooled. Air-cooled slag cannot be used for cement production.

The availability of fly ash depends on the total capacity of coal plants. It is estimated that global fly ash production reaches 500 million tonnes (ECRA, 2009). However, not all fly ash is suitable for cement production (VDZ and Penta, 2008).

Natural pozzolans are materials of volcanic origin and their availability is strongly dependent on the location. About 5.6 Mtonnes of natural pozzolans are produced worldwide (USGS, 2013b).

Another simple way to reduce the clinker content is by adding limestone. Limestone is widely available to cement plants as it is the main raw material used in cement production. The limestone content in cement could be as high as 25-35% (ECRA, 2009).

A simplified way to model the change in the clinker to cement ratio could be to only consider the availability of raw materials (see Eq. 12).

$$Clinker_{ratio,t} = Clinker_{ratio,Portland} - Limestone_{ratio} - \frac{Q_{fly\ ash,t}}{Q_{cement,t}} - \frac{Q_{BFS,t}}{Q_{cement,t}} - \frac{Q_{pozzolanas,t}}{Q_{cement,t}}$$

(12)

Variable	Definition	Unit
$Q_{cement,t}$	Total cement output in year t	Mtonnes cement
$Q_{fly\ ash,t}$	Total fly ash availability in year t	Mtonnes fly ash
$Q_{BFS,t}$	Total granulated blast furnace slag availability in year t	Mtonnes BFS
$Q_{pozzolanas,t}$	Total pozzolanas availability in year t	Mtonnes pozzolanas
$Clinker_{ratio,t}$	The clinker to cement ratio in year t	%
$Clinker_{ratio,Portland}$	The clinker to cement ratio in Portland cement (95%)	%
$Limestone_{ratio}$	The possible limestone content in cement (10-35%)	%

Supplementary material

Table 22 Cement imports and exports in the various world regions (based on CEMBUREAU, 2013)

	Variable	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
World	Cement Production	1,727,278	1,841,785	2,019,558	2,185,356	2,351,981	2,615,176	2,811,547	2,842,678	3,028,164	3,330,210	3,528,789
	Total Exports	135,162	134,821	147,638	162,138	185,219	198,553	192,339	177,041	156,520	174,797	152,173
	Clinker Exports	35,701	38,747	43,682	47,482	53,840	57,728	64,476	54,863	44,562	46,788	45,554
	Total Imports	131,072	128,053	134,656	147,926	168,982	178,474	160,341	154,443	123,669	142,974	118,346
	Apparent Consumption	1,725,256	1,837,460	2,015,680	2,181,764	2,337,471	2,593,121	2,789,303	2,839,229	3,035,295	3,357,442	3,602,707
Africa	Cement Production	75,038	77,092	85,892	90,492	103,675	114,243	122,262	132,682	142,132	144,586	147,418
	Total Exports	4,494	7,891	16,737	22,890	20,756	17,180	14,620	10,636	10,542	8,120	10,026
	Clinker Exports	545	931	4,645	7,623	5,870	3,707	3,252	756	269	386	960
	Total Imports	23,087	22,461	23,986	23,217	24,927	25,083	21,479	32,243	28,387	34,053	17,697
	Apparent Consumption	90,042	90,464	98,785	103,149	115,236	126,983	138,375	147,962	167,109	181,852	182,200
America	Cement Production	218,123	217,067	218,065	231,654	247,119	257,263	264,180	257,296	226,351	238,394	247,637
	Total Exports	15,351	15,614	16,547	17,123	18,021	16,877	16,480	12,839	10,473	9,876	10,412
	Clinker Exports	2,463	2,960	3,258	2,953	2,986	2,229	2,351	2,612	1,884	1,282	1,500
	Total Imports	32,836	30,686	30,595	34,359	40,495	41,832	29,415	18,798	13,880	15,379	18,468
	Apparent Consumption	235,276	230,205	232,330	244,223	261,031	273,706	271,546	259,585	231,332	239,740	252,812
Asia	Cement Production	1,113,495	1,211,769	1,364,209	1,488,517	1,608,911	1,817,732	1,981,072	2,031,071	2,303,458	2,585,692	2,849,551
	Total Exports	67,966	65,330	65,108	69,208	90,552	110,651	107,914	95,621	77,579	96,726	83,417
	Clinker Exports	23,342	25,011	26,223	28,149	35,854	43,096	50,075	41,520	31,587	35,126	34,108
	Total Imports	41,625	39,204	41,622	46,386	57,102	59,568	53,731	50,755	44,358	58,027	49,037
	Apparent Consumption	1,089,448	1,187,770	1,341,399	1,467,416	1,577,757	1,775,603	1,940,789	2,013,478	2,292,917	2,586,237	2,795,750
	Cement Production	44,049	55,582	62,346	71,930	76,998	88,434	97,097	91,121	75,834	83,585	92,196

	Total Exports	3,686	3,775	5,017	6,011	7,466	7,973	6,456	4,089	4,671	3,568	2,718
	Clinker Exports	707	460	420	696	1,103	674	573	265	1,576	1,981	934
	Total Imports	1,528	1,463	1,869	3,051	4,616	5,559	8,940	13,633	7,798	7,130	7,788
	Apparent Consumption	42,633	53,861	59,662	68,959	75,753	85,998	100,030	100,340	78,632	86,499	97,009
Europe	Cement Production	268,764	271,404	279,755	292,761	304,872	326,973	336,268	319,627	269,741	268,295	274,125
	Total Exports	43,134	41,892	43,986	46,756	48,328	45,790	46,720	53,728	53,085	56,321	48,135
	Clinker Exports	9,064	9,765	9,488	8,733	9,095	8,695	8,796	9,934	10,731	9,990	8,983
	Total Imports	31,439	32,705	34,803	38,192	39,745	44,309	44,305	35,706	26,763	25,266	26,282
	Apparent Consumption	259,551	264,897	272,276	285,207	295,086	319,669	326,206	304,957	254,084	251,488	258,195
Oceania	Cement Production	7,809	8,871	9,291	10,003	10,405	10,530	10,667	10,880	10,648	9,658	10,058
	Total Exports	531	319	243	151	97	81	149	129	170	186	183
	Clinker Exports	287	79	67	24	35	1	1	41	91	3	2
	Total Imports	557	1,534	1,780	2,722	2,098	2,124	2,470	3,310	2,483	3,119	6,862
	Apparent Consumption	8,307	10,263	11,229	12,809	12,607	11,162	12,357	12,906	11,221	11,626	16,741

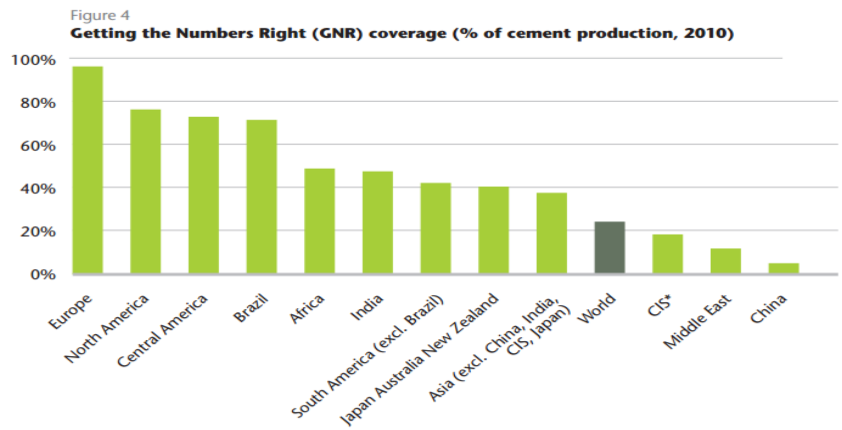

Figure 41 Getting the Numbers Right (GNR) database coverage (WBCSD, 2009)

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