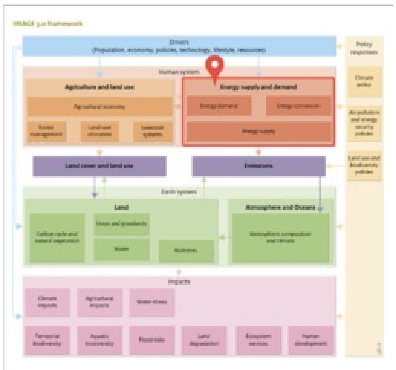
Energy supply and demand

Composition of Energy supply and demand

1. Energy conversion
2. Energy demand
3. Energy supply

Additional info

4. Technical learning



Contents [hide]

Related IMAGE components

- Energy demand
- Energy supply
- Energy conversion

Projects/Applications

- ADVANCE project

Models/Databases

- POLES model
- GCAM model

Implemented in computer model

- TIMER model

Key publications

- Van Vuuren, 2007
- De Vries et al., 2001

References

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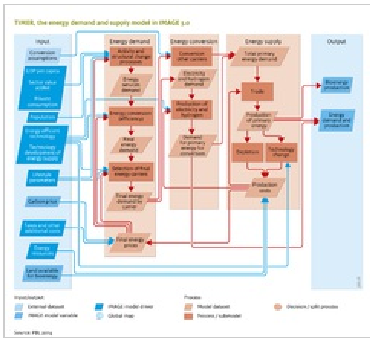

Flowchart Energy supply and demand. Overview of the IMAGE/TIMER model

Key policy issues

- How can energy supply and demand become more sustainable, balancing human development, security of supply, and concerns about climate change and air pollution?
- What transitions in the energy system would meet long-term climate goals?
- How are these strategies affected by uncertainties in the energy system?

Description of Energy supply and demand

Energy consumption and production constitutes a central component in discussions on sustainable development. Without the use of energy most human activities are impossible. Hence, securing a reliable and affordable supply of fit-for-purpose energy is an important element of countries' economic and energy policies. Three-quarters of the world's energy supply is fossil fuel. However, over time, depletion of fossil fuel resources is expected to lead to rising prices at least for oil, and easily accessible resources will be concentrated in a decreasing number of countries. Energy consumption and production is also important for environmental reasons –fuel combustion is the single most important source of local and regional air pollution and greenhouse gas emissions.

The future of the global energy system is highly uncertain and depends on factors such as technological innovations and breakthroughs, socio-economic developments, resource availability and societal choices. Exploring different scenarios for developments around the use and supply of energy provides information for decision-makers to base strategic policy decisions.

The energy supply and demand model (TIMER)

The IMage Energy Regional model, also referred to as TIMER, has been developed to explore scenarios for the energy system in the broader context of the IMAGE global environmental assessment framework (De Vries et al., 2001; Van Vuuren, 2007). TIMER describes 12 primary energy carriers in 26 world regions and is used to analyse long-term trends in energy demand and supply in the context of the sustainable development challenges[1]. The model simulates long-term trends in energy use, issues related to depletion, energy-related greenhouse gas and other air polluting emissions, together with land-use demand for energy crops. The focus is on dynamic relationships in the energy system, such as inertia and learning-by-doing in capital stocks, depletion of the resource base and trade between regions.

Similar to other IMAGE components, TIMER is a simulation model. The results obtained depend on a single set of deterministic algorithms, according to which the system state in any future year is derived entirely from previous system states. In this respect, TIMER differs from most macroeconomic models, which let the system evolve on the basis of minimising cost or maximising utility under boundary conditions. As such, TIMER can be compared to energy simulation models, such as POLES (Criqui et al., 2003) and GCAM (Thomson et al., 2011).

1. ↑ The words energy demand and energy use are often used interchangeably. However, in the past data were about statistical energy use. For the future, trends were extrapolated and denoted as energy demand, which in the model is assumed to be fully supplied and thus equal to use.

Overview of TIMER

The energy model has three components: energy demand; energy conversion; and energy supply (see Figure Flowchart). The energy demand component describes how energy demand is determined for five economic sectors -industry, transport, residential, services and other sectors. The energy conversion components describes how carriers such as electricity and hydrogen are produced. Finally, the energy supply modules describe the production of primary energy carriers, and calculate prices endogenously for both primary and secondary energy carriers that drive investment in the technologies associated with these carriers. The energy flows in all three main components allow calculation of greenhouse gas and air pollutant emissions.

The energy model TIMER focuses on long-term trends in energy supply and demand. It was mainly developed for analysing climate mitigation strategies and has also been used to explore other sustainability issues. These characteristics impose some limitations on the model. Firstly, the model cannot be used to examine macroeconomic consequences of mitigation strategies, such as GDP losses, because other aspects of the economy are not included. Secondly, the strategies depicted by the model are not necessarily optimal from an inter-temporal perspective because as a simulation model, there is no information on future development in a scenario (myopic). Instead, decisions are made on the basis of available model information at that time in the scenario. Finally, although the model has been used to analyse sustainability issues other than climate change, still much less options have been included to explore such policies (see Air pollution and energy policies).

Input/Output Table

Input Energy supply and demand component

IMAGE model drivers and variables	Description	Source
Energy resources	Volume of energy resource per carrier, region and supply cost class (determines depletion dynamics).	Drivers
GDP per capita	Gross Domestic Product per capita, measured as the market value of all goods and services produced in a region in a year, and is used in the IMAGE framework as a generic indicator of economic activity.	Drivers
Lifestyle parameters	Lifestyle parameters influence the relationship between economic activities and demand for energy.	Drivers
Population	Number of people per region.	Drivers
Private consumption	Private consumption reflects expenditure on private household consumption. It is used in IMAGE as a driver of energy.	Drivers
Sector value added	Value Added for economic sectors: Industry (IVA), Services (SVA) and Agriculture (AVA). These variables are used in IMAGE to indicate economic activity.	Drivers
Technology development of energy conversion	Learning curves and exogenous learning that determine technology development.	Drivers
Technology development of energy supply	Learning curves and exogenous learning that determine technology development.	Drivers
Carbon price	Carbon price on the international trading market (in USD in 2005 per tonne C-eq) calculated from aggregated regional permit demand and supply curves derived from marginal abatement costs.	Climate policy
Land supply for bioenergy - grid	Land available for sustainable bioenergy production (abandoned agricultural land and non-forested land).	Land cover and land use

External datasets	Description	Source
Conversion assumptions	Conversion assumptions.	

Output Energy supply and demand component

IMAGE model variables	Description	Use
Bioenergy production	Total bioenergy production.	› Land-use allocation
Energy demand and production	Aggregated energy demand and production indicators from the energy model.	Final output

Composition of Energy supply and demand

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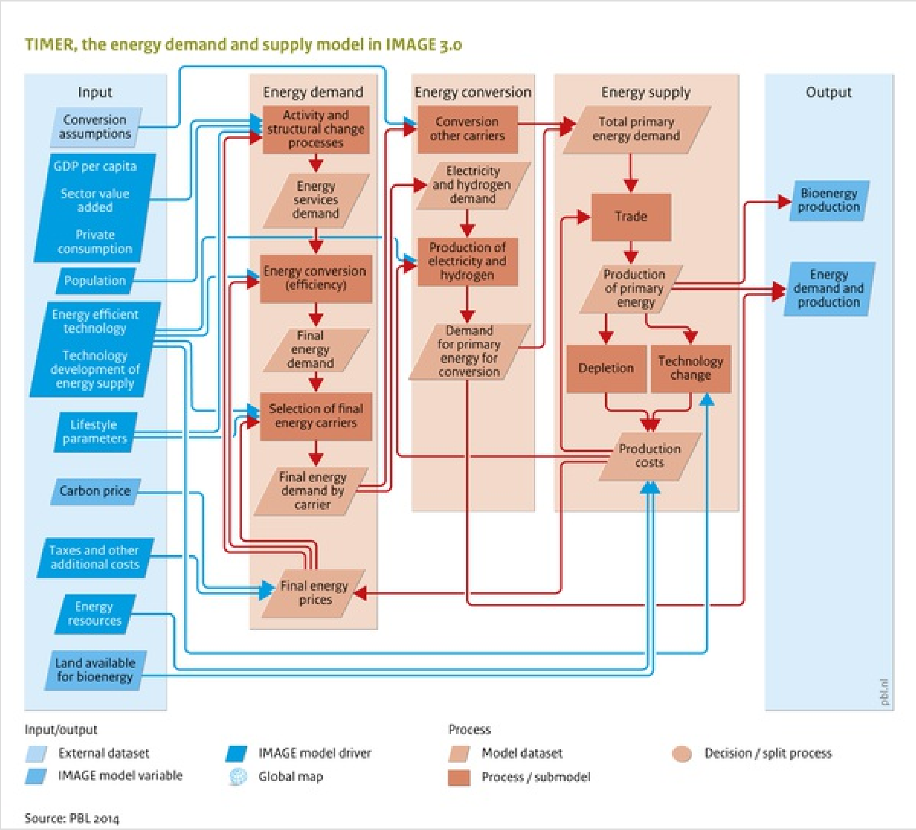
Additional info

4. Technical learning

Category: AggregatedComponent

Flowchart Energy supply and demand



Caption: Flowchart Energy supply and demand. Overview of the IMAGE/TIMER model

Figure is used on page(s): Energy supply and demand

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Energy demand

Parts of Energy demand

1. **Introduction page**
2. Model description
3. Policy issues
4. Data, uncertainty and limitations
5. Overview of references

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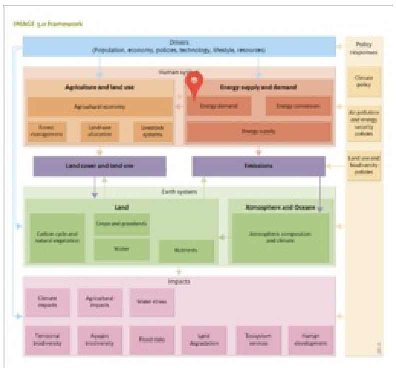


Key policy issues

- How will energy demand evolve particularly in emerging and medium- and low-income economies?
- What is the mix of end-use energy carriers to meet future energy demand?
- How can energy efficiency contribute to reducing the growth rate of energy demand and mitigate pressures on the global environment?

Related IMAGE components

- Energy supply and demand
- Energy conversion
- Energy supply
- Drivers
- Human development
- Forest management

Projects/Applications

- Roads from Rio+20 (2012) project
- EU Resource efficiency (2011) project
- ADVANCE project

Implemented in computer model

- TIMER model

Key publications

- Daioglou et al., 2012
- Girod et al., 2012
- Van Ruijven et al., 2012

Introduction

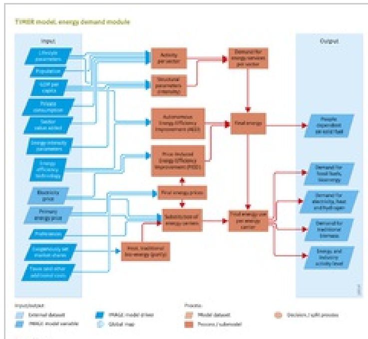
Global energy use has increased rapidly since the industrial revolution. For a historical perspective, most increases have occurred in high-income regions but more recently, the largest increase is in emerging economies. With the aspirations for income growth in medium- and low-income countries, energy demand is to be expected to grow in the coming decades, with major implications for sustainability.

Energy demand sectors and processes

In the TIMER energy demand module, final energy demand is simulated as a function of changes in population, economic activity and energy intensity (see flowchart). Five economic sectors are considered: industry; transport; residential; public and private services; and other sectors mainly agriculture. In each sector, final energy use is driven by the demand for energy services, such as motor drive, mass displacement, chemical conversions, lighting, heating and cooling. Energy demand is considered as a function of three groups of parameters and processes:

- activity data, for example on population and income, and more explicit activity indicators, such as steel production;
- long-term trends that determine the intensity of use, for example, economic structural change (SC), autonomous energy efficiency improvement (AEEI) and price-induced energy efficiency improvement (PIEEI);
- price-based fuel substitution (the choice of energy carrier on the basis of its relative costs).

These factors are implemented in different ways in the various sectors. In some sectors, a detailed end-use service-oriented modelling approach is used while in other sectors, the description is more generic and aggregate. Energy prices link the demand module with other parts of the energy model, as they respond dynamically to changes in demand, supply and conversion.



Some sectors are represented in a generic way as shown here, the sectors transport, residential and heavy industry are modelled in specific modules.

Input/Output Table

Input Energy demand component

IMAGE model drivers and variables	Description	Source
Energy efficiency technology	Model assumptions determining future development of energy efficiency.	Drivers
Energy intensity parameters	Set of parameters determining the energy use per unit of economic activity (in absence of technical energy efficiency improvements).	Drivers
GDP per capita	Gross Domestic Product per capita, measured as the market value of all goods and services produced in a region in a year, and is used in the IMAGE framework as a generic indicator of economic activity.	Drivers

indicator of economic activity.

IMAGE model drivers and variables	Description	Source
Lifestyle parameters	Lifestyle parameters influence the relationship between economic activities and demand for energy.	Drivers
Population	Number of people per region.	Drivers
Preferences	Non-price factors determining market shares, such as preferences, environmental policies, infrastructure and strategic considerations, used for model calibration.	Drivers
Private consumption	Private consumption reflects expenditure on private household consumption. It is used in IMAGE as a driver of energy.	Drivers
Sector value added	Value Added for economic sectors: Industry (IVA), Services (SVA) and Agriculture (AVA). These variables are used in IMAGE to indicate economic activity.	Drivers
Taxes and other additional costs	Taxes on energy use, and other additional costs	Drivers
Electricity price	The price of electricity.	Energy conversion
Primary energy price	The price of primary energy carriers based on production costs.	Energy supply

External datasets	Description	Source
Exogenously set market shares	Market shares of traditional biomass and secondary heat, for all demand sectors except the residential sector, exogenous scenario parameter.	IEA

Output Energy demand component

IMAGE model variables	Description	Use
People dependent on solid fuel	Proportion of population using traditional biomass and coal for cooking and heating.	› Human development
Energy and industry activity level	Activity levels in the energy and industrial sector, per process and energy carrier, for example, the combustion of petrol for transport or the production of crude oil.	› Emissions
Demand for electricity, heat and hydrogen	The demand for production of electricity, heat and hydrogen.	› Energy conversion
Demand traditional biomass	Regional demand for traditional bioenergy.	› Forest management
Demand for fossil fuels and bioenergy	The demand for the production of fossil fuels and bioenergy.	Final output

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Category: Component

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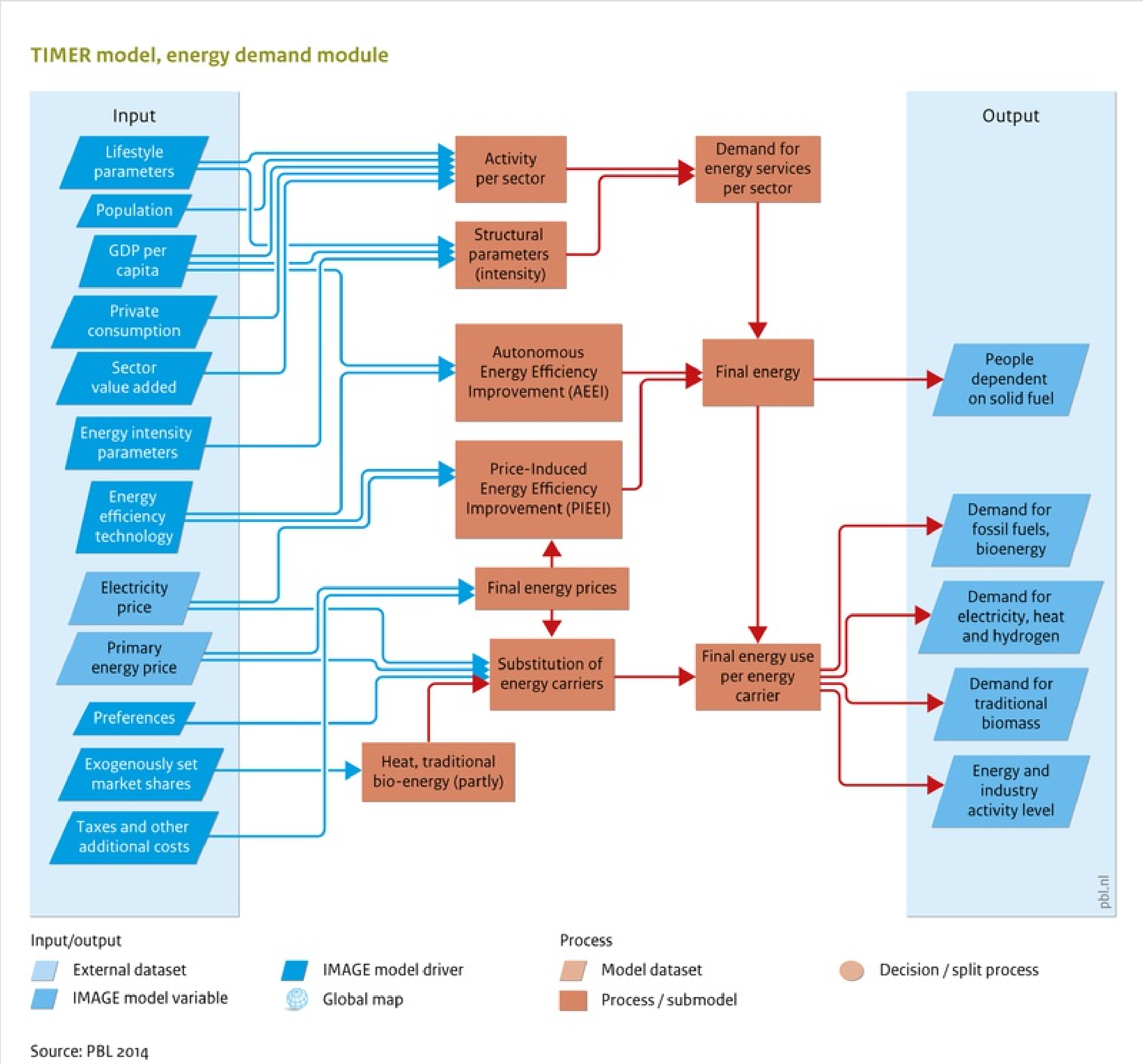
Flowchart Energy demand



Caption: Some sectors are represented in a generic way as shown here, the sectors transport, residential and heavy industry are modelled in specific modules.

Figure is used on page(s): Energy demand

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Energy demand/Description

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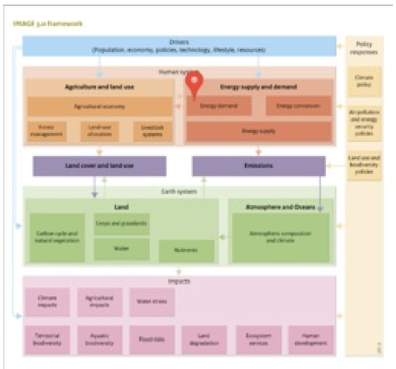

Model description of Energy demand

The energy demand module has aggregated formulations for some sectors and more detailed formulations for other sectors. In the description that follows, the generic model is presented which is used for the service sector, part of the industry sector (light) and in the category other sectors. Next, the more technology detailed sectors of residential energy use, heavy industry and transport are discussed in relation to the elements of the generic model.

In the generic module, demand for final energy is calculated for each region (R), sector (S) and energy form (F, heat or electricity) according to:

$$SE_{R,S,F} = \frac{POP_R(t) * \frac{ACT}{POP}_{R,S}(t) * SC_{R,S,F}(t) * AEEI_{R,S,F}(t) * PIEEI_{R,S,F}(t)}{\sum_{EC} \eta_{R,S,C(t)} * MS_{R,S,C(t)}}$$

Equation 1, in which:

- SE represents final energy;
- POP represents population;
- ACT/POP the sectoral activity per capita;
- SC a factor capturing intra-sectoral structural change;
- AEEI the autonomous energy efficiency improvement;
- PIEEI the price-induced energy efficiency improvement.

In the denominator:

- η is the end-use efficiency of energy carriers used in, for example, boilers and stoves;
- MS represents the share of each energy carrier.

Population and economic activity levels are exogenous inputs into the module. Each of the other dynamic factors in equation 1 are briefly discussed below.

Structural change (SC)

In each sector, the mix of activities changes as a function of development and time. These changes, referred to as structural change, may influence the energy intensity of a sector. For instance, using more private cars for transport instead of buses tends to increase energy intensity. Historically, in several sectors, as a consequence of the structural changes in the type of activities an increase in energy intensity can be observed followed by a decrease. Evidence of this trend is more convincing in industry with shifts from very basic to heavy industry and finally to industries with high value-added products than in other sectors, such as transport where historically, energy intensity has mainly been increasing (De Vries et al., 2001).

Based on the above, in *generic model formulations*, energy intensity is driven by income, assuming a peak in energy intensity, followed by saturation of energy demand at a constant per capita energy service level. In the calibration process, the choice of parameters may lead, for instance, to a peak in energy intensity higher than current income levels. In the technology-detailed energy demand

Related IMAGE components

- Drivers
- Energy conversion
- Energy supply
- Energy supply and demand
- Forest management
- Human development

Projects/Applications

- ADVANCE project
- EU Resource efficiency (2011) project
- Roads from Rio+20 (2012) project

Implemented in computer model

- TIMER model

Key publications

- Daioglou et al., 2012
- Girod et al., 2012
- Van Ruijven et al., 2012

References

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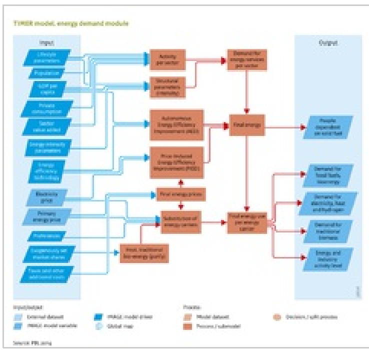

Some sectors are represented in a generic way as shown here, the sectors transport, residential and heavy industry are modelled in specific modules.

(see below), structural change is captured by other equations that describe the underlying processes explicitly (e.g., modal shift in transport).

Autonomous Energy Efficiency Increase (AEEI)

This is a multiplier used in the generic energy demand module to account for efficiency improvement as a result of technology improvement, independent of prices. In general, current appliances are more efficient than those available in the past.

The autonomous energy efficiency increase for new capital is a fraction (f) of the economic growth rate based on the formulation of Richels et al. (2004). The fraction varies between 0.45 and 0.30 (based on literature data) and is assumed to decline with time because the scope for further improvement is assumed to decline. Efficiency improvement is assumed for new capital. Autonomous increase in energy efficiency for the average capital stock is calculated as the weighted average value of the AEEI values of the total in capital stock, using the vintage formulation. In the *technology-detailed submodules*, the autonomous energy efficiency increase is represented by improvement in individual technologies over time.

Price-Induced Energy Efficiency Improvement (PIEEI)

This multiplier is used to describe the effect of rising energy costs in the form of induced investments in energy efficiency by consumers. It is included in the *generic formulation* using an energy conservation cost curve. In the *technology-detailed submodules*, this multiplier is represented by competing technologies with different efficiencies and costs.

Substitution

Demand for secondary energy carriers is determined on the basis of demand for energy services and the relative prices of the energy carriers. For each energy carrier, a final efficiency value (η) is assumed to account for differences between energy carriers in converting final energy into energy services. The indicated market share (IMS) of each fuel is determined using a multinomial logit model that assigns market shares to the different carriers (i) on the basis of their relative prices in a set of competing carriers (j).

$$IMS_i = \exp(\lambda c_i)/\Sigma_j \exp(\lambda c_j)$$

IMS is the indicated market share of different energy carriers or technologies and c is their costs. In this equation, λ is the so-called logit parameter, determining the sensitivity of markets to price differences.

The equation takes account of direct production costs and also energy and carbon taxes and premium values. The last two reflect non-price factors determining market shares, such as preferences, environmental policies, infrastructure (or the lack of infrastructure) and strategic considerations. The premium values are determined in the model calibration process in order to correctly simulate historical market shares on the basis of simulated price information. The same parameters are used in scenarios to simulate the assumption on societal preferences for clean and/or convenient fuels. However, the market shares of traditional biomass and secondary heat are determined by exogenous scenario parameters (except for the residential sector discussed below). Non-energy use of energy carriers is modelled on the basis of exogenously assumed intensity of representative non-energy uses (chemicals) and on a price-driven competition between the various energy carriers (Daioglou et al., 2014).

Heavy industry

The heavy industry submodule was include for the steel and cement sectors (Van Ruijven et al., 2013). These two sectors represented about 8% of global energy use and 13% of global anthropogenic greenhouse gas emissions in 2005. The generic structure of the energy demand module was adapted as follows:

- Activity is described in terms of production of tonnes cement and steel. The regional demand for these commodities is determined by a relationship similar to the formulation of the structural change discussed above. Both cement and steel can be traded but this is less important for cement. Historically, trade patterns have been prescribed but future production is assumed to shift slowly to producers with the lowest costs.
- The demand after trade can be met from production that uses a mix of technologies. Each technology is characterised by costs and energy use per unit of production, both of which decline slowly over time. The actual mix of technologies used to produce steel and cement in the model is derived from a multinominal logit equation, and results in a larger market share for the technologies with the lowest costs. The autonomous improvement of these technologies leads to an autonomous increase in energy efficiency. The selection of technologies represents the price-induced improvement in energy efficiency. Fuel substitution is partly determined on the basis of price, but also depends on the type of technology because some technologies can only use specific energy carriers (e.g., electricity for electric arc furnaces).

Transport

The transport submodule consists of two parts - passenger and freight transport. A detailed description of the passenger transport (TRAVEL) is provided by Girod et al. (2012). There are seven modes - foot, bicycle, bus, train, passenger vehicle, high-speed train, and aircraft. The structural change (SC) processes in the transport module are described by an explicit consideration of the modal split. Two main factors govern model behaviour, namely the near-constancy of the travel time budget (TTB), and the travel money budget (TMB) over a large range of incomes. These are used as constraints to describe transition processes among the seven main travel modes, on the basis of their relative costs and speed characteristics and the consumer preferences for comfort levels and specific transport modes.

The freight transport submodule is a simpler structure. Service demand is projected with constant elasticity of the industry value added for each transport mode. In addition, demand sensitivity to transport prices is considered for each mode, depending on its share of energy costs in the total service costs.

The efficiency changes in both passenger and freight transport represent the autonomous increase in energy efficiency, and the price-induced improvements in energy efficiency improvement parameters. These changes are described by substitution processes in explicit technologies, such as vehicles with different energy efficiencies, costs and fuel type characteristics compete on the basis of preferences and total passenger-kilometre costs, using a multinomial logit equation. The efficiency of the transport fleet is determined by a weighted average of the full fleet (a vintage model, giving an explicit description of the efficiency in all single years). As each type of vehicle is assumed to use only one fuel type, this process also describes the fuel selection.

Residential energy use

The residential submodule describes the energy demand from household energy functions of cooking appliances, space heating and cooling, water heating and lighting. These functions are described in detail elsewhere (Daioglou et al., 2012; Van Ruijven et al., 2011).

Structural change in energy demand is presented by modelling end-use household functions:

- Energy service demand for space heating is modelled using correlations with floor area, heating degree days and energy intensity, the last including building efficiency improvements.
- Hot water demand is modelled as a function of household income and heating degree days.
- Energy service demand for cooking is determined on the basis of an average constant consumption of 3 MJUE/capita/day.
- Energy use related to appliances is based on ownership, household income, efficiency reference values, and autonomous and price-induced improvements. Space cooling follows a similar approach, but also includes cooling degree days (Isaac and Van Vuuren, 2009).
- Electricity use for lighting is determined on the basis of floor area, wattage and lighting hours based on geographic location.

Efficiency improvements are included in different ways. Exogenously driven energy efficiency improvement over time are used for appliances, light bulbs, air conditioning, building insulation and heating equipment, Price-induced energy efficiency improvements (PIEEI) occur by explicitly describing the investments in appliances with a similar performance level but with different energy and investment costs. For example, competition between incandescent light bulbs and more energy-efficient lighting is determined by changes in energy prices.

The model distinguishes five income quintiles for both the urban and rural population. After determining the energy demand per function for each population quintile, the choice of fuel type is determined on the basis of relative costs. This is based on a multinomial logit formulation for energy functions that can involve multiple fuels, such as cooking and space heating. In the calculations, consumer discount rates are assumed to decrease along with household income levels, and there will be increasing appreciation of clean and convenient fuels (Van Ruijven et al., 2011). For developing countries, this endogenously results in the substitution processes described by the energy ladder. This refers to the progressive use of modern energy types as incomes grow, from traditional bioenergy to coal and kerosene, to energy carriers such as natural gas, heating oil and electricity.

The residential submodule also includes access to electricity and the associated investments (Van Ruijven et al., 2012). Projections for access to electricity are based on an econometric analysis that found a relation between level of access , and GDP per capita and population density. The investment model is based on population density on a 0.5 x 0.5 degree grid, from which a stylised power grid is derived and analysed to determine investments in low-, medium- and high-voltage lines and transformers. See additional info on Grid and infrastructure

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5. Overview of references

Additional info

6. Grid and infrastructure

Category: ComponentDescription

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Energy demand/Policy issues

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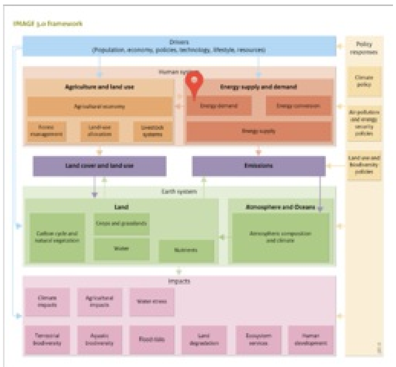


Related IMAGE components
- Drivers
- Energy conversion
- Energy supply
- Energy supply and demand
- Forest management
- Human development

Projects/Applications
- ADVANCE project
- EU Resource efficiency (2011) project
- Roads from Rio+20 (2012) project

Implemented in computer model
- TIMER model

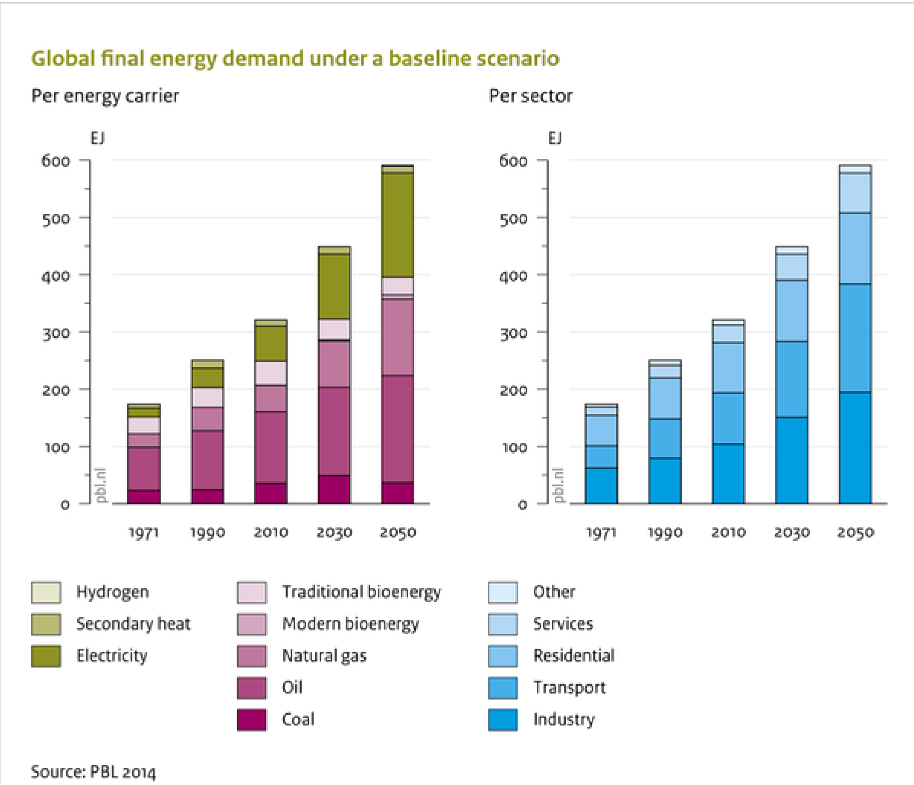
Key publications
- Daioglou et al., 2012
- Girod et al., 2012
- Van Ruijven et al., 2012

References

[Expand]

Baseline developments

The model shows that under a typical baseline scenario such as the one of the Rio+20 study, energy demand is projected to grow significantly during the 21st century. Most growth will be driven by an increase in energy use in low-income countries. Per capita use in high-income countries is projected to remain more or less constant, consistent with recent historical trends. The increase in energy demand in the first half of the century will be mostly met by fossil fuels and electricity. In this model simulation, hydrogen becomes competitive in the transport sector in the second half of the century, as a result of increasing oil prices and the assumed progress in hydrogen technologies. An alternative assumption could result in a similar role for electricity.



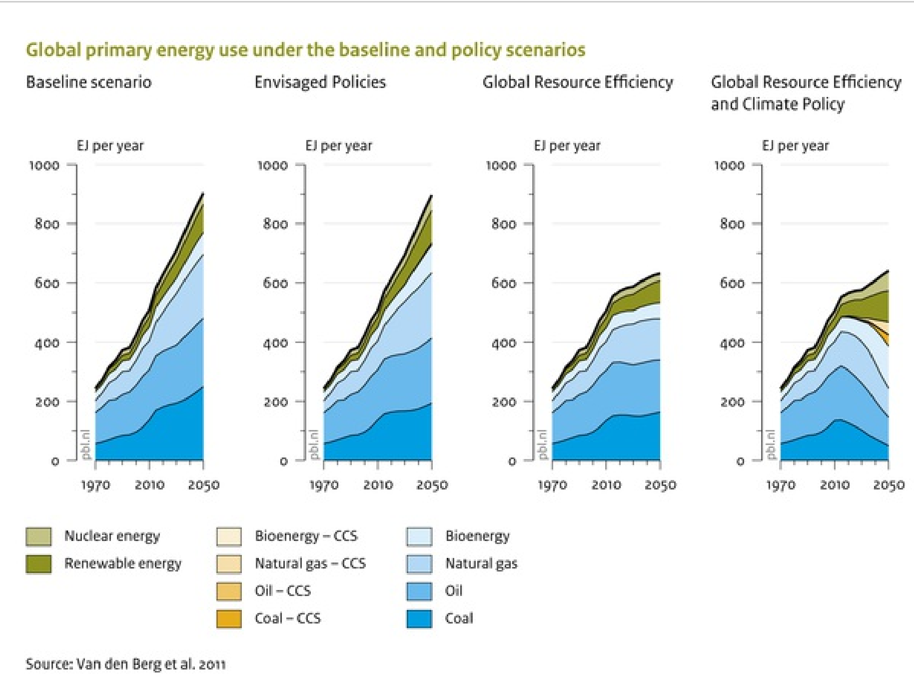
Between 2010 and 2050 energy demand for transport and industry, and for natural gas and electricity contribute most to the overall increase.

Policy interventions

Various policy interventions can be implemented in the energy demand submodules in different ways (see also the Policy interventions Table below):

- Energy tax and carbon tax. This changes the prices for the energy carriers influences the choice of technology.
- Discount rate/payback time. In the residential submodule , the perceived costs of capital (discount rate) influence the extent of energy efficiency improvement (PIEEI) and the choice of fuel and/or technology in the residential submodule.
- Preferences. Fuel choice can be influenced by correction factors, representing aspects that influence fuel choice but are not incorporated in the price, such as fuel characteristics (e.g., cleanliness, availability), comfort and speed considerations, and infrastructure.
- Efficiency standards. Such improvements can be introduced for the submodules that focus on specific technologies, for example, in transport, heavy industry and households.
- Enforced market shares of fuel types. Such an analysis could, for instance, provide insight into the implications in the model of increasing the use of biofuels, electricity or hydrogen (Van Ruijven et al., 2007).

The PBL study Resource Efficiency (Van den Berg et al., 2011) provides an example of how TIMER can be used to explore the impact of radically improving energy efficiency. The study included an accelerated trend to best available technologies in iron and steel production and other industries, most efficient passenger vehicles and aircraft, a moderate shift from aircraft to high-speed trains, and building highly efficient housing (mostly insulation measures). The study also assumed that newly installed power plants will be based on the best available technologies. The measures in this global energy efficiency scenario will considerably reduce energy use than under the baseline scenario. Primary energy consumption will be reduced by about 30% by 2050.



The 'envisaged policies' scenario includes currently planned policies, the 'global resource efficiency' scenario assumes ambitious energy efficiency policies, and the 'global resource efficiency and climate policy' scenario additionally assumes policies to meet the 2 °C target. Total primary energy use could be significantly reduced by policies on energy efficiency, whereas additional climate policy would mostly affect the type of resources used. (Van den Berg et al., 2011b)

Effects of policy interventions on this component

Policy intervention	Description	Effect
Carbon tax (*)	A tax on carbon leads to higher prices for carbon intensive fuels (such as fossil fuels), making low-carbon alternatives more attractive.	The higher fossil fuel prices result in a shift towards less carbon-intensive energy carriers and (assuming a higher overall energy price) more energy efficiency. There can also be changes in end-use technologies (e.g. electric cars in the transport sector, blast furnaces with CCS to produce iron and steel).
Change market shares of fuel types (*)	Exogenously set the market shares of certain fuel types. This can be done for specific analyses or scenarios to explore the broader implications of increasing the use of, for instance, biofuels, electricity or hydrogen and reflects the impact of fuel targets. (Reference: Van Ruijven et al., 2007)	The share of the fuel in final energy consumption will be at least equal to the target.
Change the use of electricity and hydrogen	It is possible to promote the use of electricity and hydrogen at the end-use level.	An increase in the use of electricity and hydrogen at the end use level. Given the high flexibility in the choice of feedstock in electricity and hydrogen production this can increase the ability of the total system to reduce greenhouse gas emissions in a mitigation scenario.
Improving energy efficiency (*)	Exogenously set improvement in efficiency. Such improvements can be introduced for the submodels that focus on particular technologies, for example, in transport, heavy industry and households submodels.	More efficient use of final energy, change in end use technologies, which leads to lower energy demand.

Policy intervention	Description	Effect
Provision on improved stoves for traditional bio-energy (*)	Increases the efficiency of bio-energy use.	Reduces demand for bio-energy.
Subsidies on modern energy (*)	Reduces the costs of modern energy to reduce traditional energy use (can be targeted to low income groups).	Reduces traditional energy use, while increasing modern energy use.

(*) Implemented in this component.

Parts of Energy demand

Energy demand/Data uncertainties limitations

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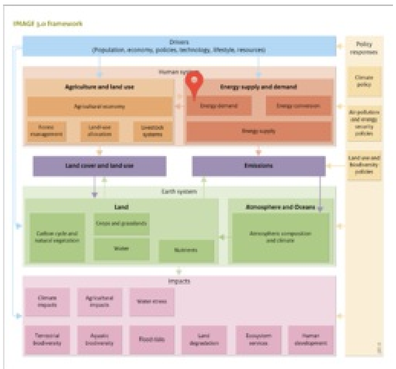

Data

The energy demand module has been calibrated for the 1971–2007 period in order to reproduce historical trends in fuel and electricity use (see papers on individual model components, such as Van Ruijven et al., 2010a). Using the historical input data on population and value added and the calculated energy prices as given, other drivers and model parameters were varied systematically within the range of values derived from the literature, in order to improve the fit (Van Ruijven et al., 2010a; Van Ruijven et al., 2010b).

The primary data source on energy use was the International Energy Agency (IEA). These data were complemented with data from other sources, such as steel and cement demand and production, and transport data from as described in the references of the different model components. The residential submodule uses data from national statistical agencies and household surveys (Van Ruijven et al., 2010a).

Uncertainties

The main uncertainties in modelling energy demand relate to the interpretation of historical trends, for instance, on the role of structural change, autonomous energy efficiency increases and price-induced efficiency improvements and their projection for the future (Van Vuuren et al., 2008).

Two uncertainties are the existence of saturation levels and the potential for efficiency increases. The representation in TIMER is based on the assumption that demand for energy services tends to become saturated at some point. This is based on physical considerations and historical trends in sectors, such as residential energy use. However, economic models assume that income and energy use remain coupled, often even at constant growth elasticities. Evidence for a constant growth can also be found in some sectors, notably transport and services.

In deciding between these different dynamics, the extent to which historical trends would be the best guide for the future is also unclear. A similar issue concerns the role of energy efficiency. Many techno-economic analyses of efficiency potential suggest large possibilities at rather low payback times. However, from a historical perspective, investments in efficiency have been significantly lower than optimal for cost minimisation. Other factors must be assumed to play a role in the form of perceived transaction costs. A critical issue is whether this efficiency potential could be exploited in the future.

In the model calibration, there is a large degree of freedom in parameter setting so that results fit historical observations. A method has been developed to identify the implications of different outcomes of model calibrations and has been applied to the transport and residential submodules (Van Ruijven et al., 2010a; Van Ruijven et al., 2010b).

The starting point is that insufficient data are available to fully understand historic trends and calibrate global energy models. TIMER has room for different sets of parameter values that simulate historical energy use equally well, but reflect different historical interpretations and result in different future projections. The recent trend to replace some energy models by a description of end-use functions and applying physical considerations will reduce some uncertainties as this enables better estimation of reasonable saturation levels. However, this method suffers from the fact that new energy functions may be developed in the future that could increase energy demand.

Related IMAGE components
- Drivers
- Energy conversion
- Energy supply
- Energy supply and demand
- Forest management
- Human development

Projects/Applications
- ADVANCE project
- EU Resource efficiency (2011) project
- Roads from Rio+20 (2012) project

Implemented in computer model
- TIMER model

Key publications
- Daioglou et al., 2012
- Girod et al., 2012
- Van Ruijven et al., 2012

References
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Limitations

The main limitations of the TIMER energy demand model are listed in the introduction to the model. A critical factor in modelling energy demand is the level of detail, given the large number of relevant technologies. TIMER uses an intermediate approach, in which some key technologies are modelled explicitly, and others are included implicitly. For more detailed estimates of the potential of energy efficiency, it would be more appropriate to use a different model.

Parts of Energy demand

Energy demand/References

< Energy demand

Key publications

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B. van Ruijven, J.P. van der Sluijs, Detlef van Vuuren, P. Janssen, P. S. C. Heuberger, B. de Vries (2010). Uncertainty from model calibration: Applying a new method to transport energy demand modelling. Environmental Modelling and Assesment, 15(3), pp.175-188, doi: http://dx.doi.org/10.1007/s10666-009-9200-z.

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Link to PBL-website: http://www.pbl.nl/en/publications/2008/Conditional-probabilistic-estimates-of-21st-century-greenhouse-gas-emissions-based-on-the-storylines.

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M. van den Berg, J. A. Bakkes, L. Bouwman, M. Jeuken, T. Kram, K. Neumann, D.P. van Vuuren, h. Wilting (2011). EU resource efficiency perspectives in a global context, PBL Netherlands Environmental Assessment Agency, The Hague. Link to PBL-website: http://www.pbl.nl/en/publications/2011/eu-resource-efficiency-perspectives-in-a-global-context.

Category: AllReferencesPages

Energy supply

Parts of Energy supply

1. **Introduction page**
2. Model description
3. Policy issues
4. Data, uncertainty and limitations
5. Overview of references

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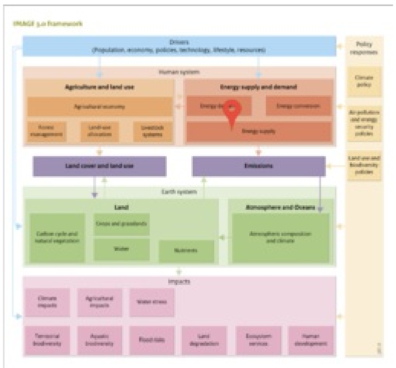


Key policy issues

- How can energy resources be exploited to meet future primary energy demand?
- How can energy supply and demand be balanced between world regions, and how will this effect security of supply?
- How rapidly can the transition to more sustainable energy supply be made?

Introduction

A key factor in future energy supply is the availability (and depletion) of various resources. One aspect is that energy resources are unevenly spread across world regions and often, poorly matched with regional energy demand. This is directly related to energy security. In representation of energy supply, the IMAGE energy model, describes long-term dynamics based on the interplay between resource depletion (upward pressure on prices) and technology development (downward pressure on prices). In the model, technology development is introduced in the form of learning curves for most fuels and renewable options. Costs decrease endogenously as a function of the cumulative energy capacity, and in some cases, assumptions are made about exogenous technology change.

Depletion is a function of either cumulative production or annual production. For example, for fossil-fuel resources and nuclear feedstock, low-cost resources are slowly being depleted, and thus higher cost resources need to be used. In annual production, for example, of renewables, attractive production sites are used first. Higher annual production levels require use of less attractive sites with less wind or lower yields.

It is assumed that all demand is always met. Because regions are usually unable to meet all of their own demand, energy carriers, such as coal, oil and gas, are widely traded. The impact of depletion and technology development lead to changes in primary fuel prices, which influence investment decisions in the end-use and energy-conversion modules Linkages to other parts of IMAGE framework include available land for bioenergy production, emissions of greenhouse gases and air pollutants (partly related to supply), and the use of land for bioenergy production (land use for other energy forms are not taken into account). Several key assumptions determine the long-term behaviour of the various energy supply submodules and are mostly related to technology development and resource base.

Related IMAGE components

- Drivers
- Land cover and land use
- Crops and grass
- Emissions
- Climate policy
- Atmospheric composition and climate
- Energy demand
- Energy conversion
- Energy supply and demand

Projects/Applications

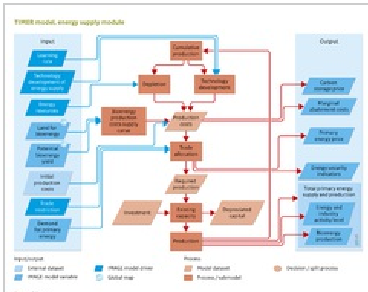
- Roads from Rio+20 (2012) project
- ADVANCE project

Implemented in computer model

- TIMER model

Key publications

- De Vries et al., 2007
- Van Vuuren et al., 2008
- Van Vuuren et al., 2009



Flowchart Energy supply. See also the Input/Output Table on the introduction page.

Input/Output Table

Input Energy supply component

IMAGE model drivers and variables	Description	Source
Energy resources	Volume of energy resource per carrier, region and supply cost class (determines depletion dynamics).	Drivers
Learning rate	Determines the rate of technology development in learning equations.	Drivers
Technology development of energy supply	Learning curves and exogenous learning that determine technology development.	Drivers
Trade restriction	Trade tariffs and barriers limiting trade in energy carriers (in energy submodel).	Drivers

IMAGE model drivers and variables	Description	Source
Demand for primary energy	Total demand for energy production. Sum of final energy demand and energy inputs into energy conversion processes.	Energy conversion
Land supply for bioenergy - grid	Land available for sustainable bioenergy production (abandoned agricultural land and non-forested land).	Land cover and land use
Potential bioenergy yield - grid	Potential yields of bioenergy crops.	Crops and grass

External datasets	Description	Source
Initial production costs	The costs of energy conversion technologies at the start of the simulation.	Various sources

Output Energy supply component

IMAGE model variables	Description	Use
Primary energy price	The price of primary energy carriers based on production costs.	Energy conversion Energy demand
Bioenergy production	Total bioenergy production.	Land-use allocation
Marginal abatement cost	Cost of an additional unit of pollution abated (CO2eq). A marginal abatement cost curve (MAC curve) is a set of options available to an economy to reduce pollution, ranked from the lowest to highest additional costs.	Climate policy
Carbon storage price	The costs of capturing and storing CO2, affecting the use of CCS technology.	Energy conversion
Energy and industry activity level	Activity levels in the energy and industrial sector, per process and energy carrier, for example, the combustion of petrol for transport or the production of crude oil.	Emissions
Energy security indicators	Indicators on the status of energy security, such as energy self-sufficiency.	Final output
Total primary energy supply	Total primary energy supply.	Final output

Parts of Energy supply

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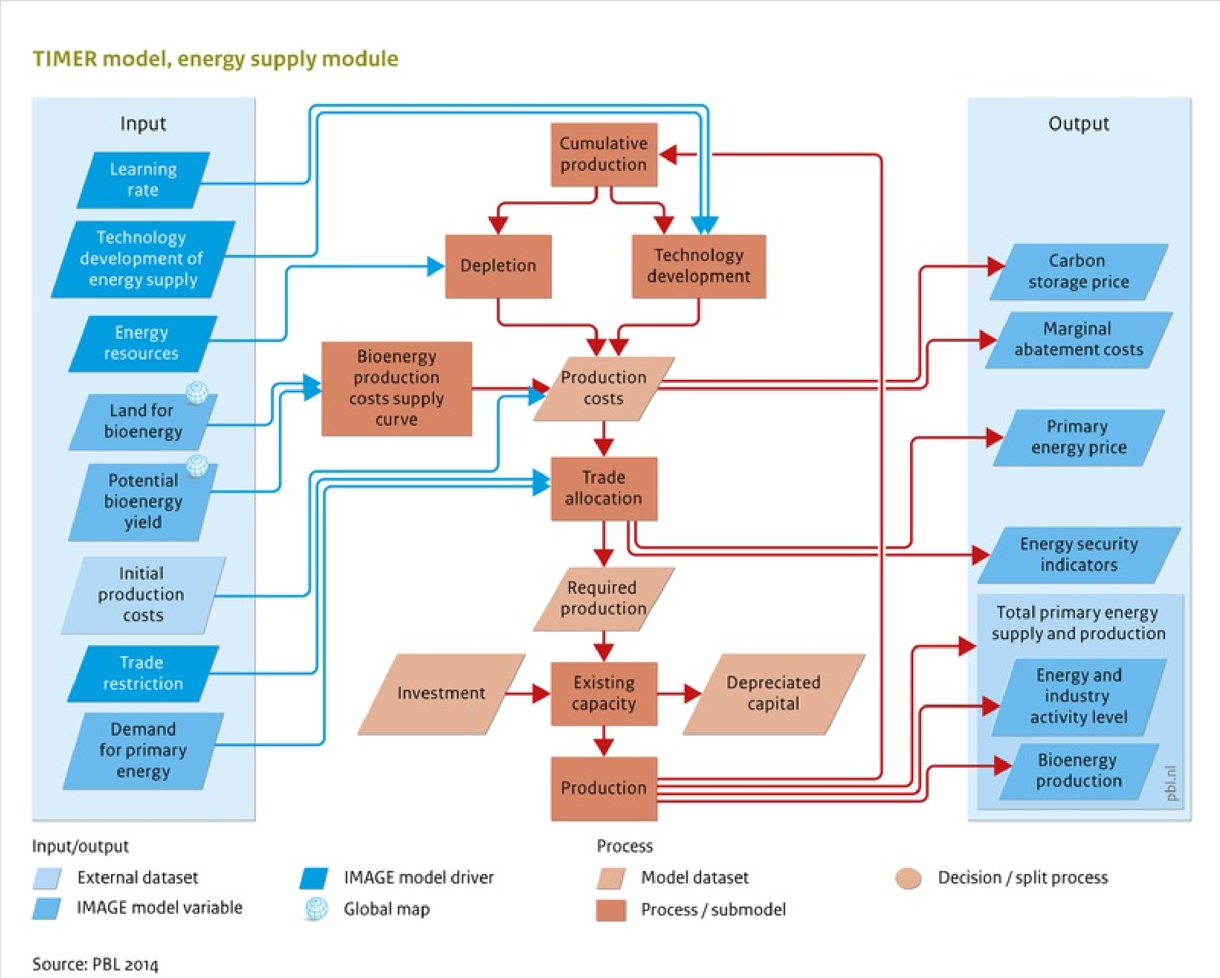
5. Overview of references

Category: Component

Flowchart Energy supply



Caption: Flowchart Energy supply. See also the Input/Output Table on the introduction page.

Figure is used on page(s): Energy supply

View Image

Energy supply/Description

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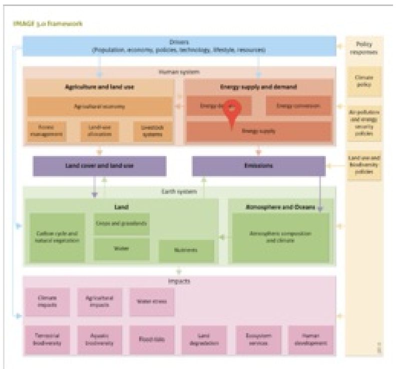

Model description of Energy supply

Fossil fuels and uranium

Depletion of fossil fuels (coal, oil and natural gas) and uranium is simulated on the assumption that resources can be represented by a long-term supply cost curve, consisting of different resource categories with increasing costs levels. The model assumes that the cheapest deposits will be exploited first. For each region, there are 12 resource categories for oil, gas and nuclear fuels, and 14 categories for coal.

A key input for each of the fossil fuel and uranium supply submodules is fuel demand (fuel used in final energy and conversion processes). Additional input includes conversion losses in refining, liquefaction, conversion, and energy use in the energy system. These submodules indicate how demand can be met by supply in a region and other regions through interregional trade.

Table: Main assumptions on fossil fuel resources (Rogner, 1997; Mulders et al., 2006)

	Oil	Natural gas	Underground coal	Surface coal
Cum. 1970-2005 production	4.4	2.1	1.6	1.1
Reserves	4.8	4.6	23.0	2.2
Other conventional resources	6.6	6.9	117.7	10.0
Unconventional resources (reserves)	2.9	6.9	25.0	233.5
Other unconventional resources	46.2	498.6	1.3	23.0
Total	65.0	519.2	168.6	270.0

Fossil fuel resources are aggregated to five resource categories for each fuel (the table above). Each category has typical production costs. The resource estimates for oil and natural gas supply imply that for conventional resources supply is limited to only two to eight times the 1970–2005 production level. Production estimates for unconventional resources are much larger, albeit very speculative. Recently, some of the occurrences of these unconventional resources have become competitive such as shale gas and tar sands. For coal, even current reserves amount to almost ten times the production level of the last three decades. For all fuels, the model assumes that, if prices increase, or if there is further technology development, the energy could be produced in the higher cost resource categories. The values presented in the table above represent medium estimates in the model, which can also use higher or lower estimates in the scenarios. The final production costs in each region are determined by the combined effect of resource depletion and learning-by-doing.

Trade

Trade is dealt with in a generic way for oil, natural gas and coal. In the fuel trade model, each region imports fuels from other regions. The amount of fuel imported from each region depends on the relative production costs and those in other regions, augmented with transport costs, using multinomial logit equations. Transport costs are calculated from representative interregional transport distances and time- and fuel-dependent estimates of the costs per GJ per kilometre.

Related IMAGE components

- Atmospheric composition and climate
- Climate policy
- Crops and grass
- Drivers
- Emissions
- Energy conversion
- Energy demand
- Energy supply and demand
- Land cover and land use

Projects/Applications

- ADVANCE project
- Roads from Rio+20 (2012) project

Implemented in computer model

- TIMER model

Key publications

- De Vries et al., 2007
- Van Vuuren et al., 2008
- Van Vuuren et al., 2009

References

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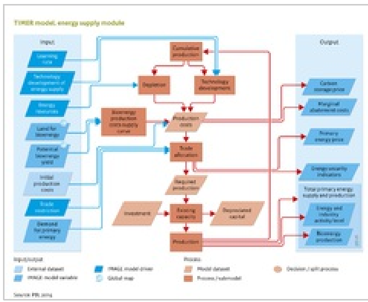

Flowchart Energy supply. See also the Input/Output Table on the introduction page.

To reflect geographical, political and other constraints in the interregional fuel trade, an additional 'cost' is added to simulate trade barriers between regions (this costs factor is determined by calibration). Natural gas is transported by pipeline or liquid-natural gas (LNG) tanker, depending on distance, with pipeline more attractive for short distances. In order to account for cartel behaviour, the model compares production costs with and without unrestricted trade. Regions that can supply at lower costs than the average production costs in importing regions (a threshold of 60% is used) are assumed to supply oil at a price only slightly below the production costs of the importing regions. Although also this rule is implemented in a generic form for all energy carriers, it is only effective for oil, where the behaviour of the OPEC cartel is simulated to some extent.

Bioenergy

The structure of the biomass submodule is similar to that for fossil fuel supply, but with the following differences (Hoogwijk, 2004):

- Depletion of bioenergy is not governed by cumulative production but by the degree to which available land is used for commercial energy crops.
- The total amount of potentially available bioenergy is derived from bioenergy crop yields calculated on a 0.5x0.5 degree grid with the IMAGE crop model for various land-use scenarios for the 21st century. Potential supply is restricted on the basis of a set of criteria, the most important of which is that bioenergy crops can only be on abandoned agricultural land and on part of the natural grassland. The costs of primary bioenergy crops (woody, maize and sugar cane) are calculated with a Cobb-Douglas production function using labour , land rent and capital costs as inputs. The land costs are based on average regional income levels per km^2, which was found to be a reasonable proxy for regional differences in land rent costs. The production functions are calibrated to empirical data (Hoogwijk, 2004).
- The model describes the conversion of biomass (including residues, in addition to wood crops, maize and sugar cane) to two generic secondary fuel types: bio-solid fuels used in the industry and power sectors; and liquid fuel used mostly in the transport sector.
- The trade and allocation of biofuel production to regions is determined by optimisation. An optimal mix of bio-solid and bio-liquid fuel supply across regions is calculated, using the prices of the previous time step to calculate the demand.

The production costs for bioenergy are represented by the costs of feedstock and conversion. Feedstock costs increase with actual production as a result of depletion, while conversion costs decrease with cumulative production as a result of 'learning by doing'. Feedstock costs include the costs of land, labour and capital, while conversion costs include capital, O&M and energy use in this process. For both steps, the associated greenhouse gas emissions (related to deforestation, N_2O from fertilisers, energy) are estimated (see Component Emissions), and are subject to carbon tax, where relevant.

Other renewable energy

Potential supply of renewable energy (wind, solar and bioenergy) is estimated generically as follows (Hoogwijk, 2004; De Vries et al., 2007):

1. Physical and geographical data for the regions considered are collected on a 0.5x0.5 degree grid. The characteristics of wind speed, insulation and monthly variation are taken from the digital database constructed by the Climate Research Unit (New et al., 1997).
2. The model assesses the part of the grid cell that can be used for energy production, given its physical–geographic (terrain, habitation) and socio-geographical (location, acceptability) characteristics. This leads to an estimate of the geographical potential. Several of these factors are scenario-dependent. The geographical potential for biomass production from energy crops is estimated using suitability/availability factors taking account of competing land-use options and the harvested rain-fed yield of energy crops.
3. Next, we assume that only part of the geographical potential can be used due to limited conversion efficiency and maximum power density, This result of accounting for these conversion efficiencies is referred to as the technical potential.
4. The final step is to relate the technical potential to on-site production costs. Information at grid level is sorted and used as supply cost curves to reflect the assumption that the lowest cost locations are exploited first. Supply cost curves are used dynamically and change over time as a result of the learning effect.

Energy supply/Policy issues

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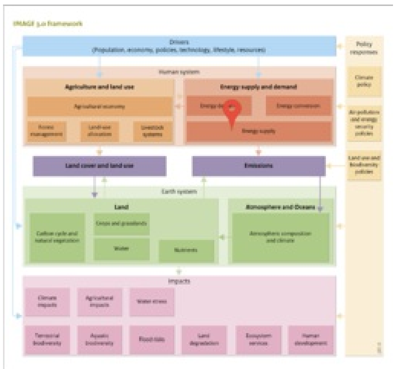

Baseline developments

Under the baseline scenario, demand for energy increases rapidly, and as a consequence, supply is projected to increase in the coming decades for all energy supply options. Under the baseline scenario, energy demand is mostly met by fossil fuels but shifts in dominant energy carriers and main supply regions are also projected. For coal, the model indicates continuous rise in production, mostly in the regions already producing the largest shares of global output. For oil, the model also shows continuous increase in production in the coming decades, with an increase in unconventional sources, mainly from Canada and South America.

Natural gas is expected to rise faster in production because it is presumed to be more abundant and increasingly more cost competitive, with unconventional sources becoming increasingly more important. Main gas producers are the United States, the former Soviet Union and increasingly the Middle East.

Production of modern types of bioenergy is constantly increasing and in different parts of the world. For solar and wind, the most rapid increase so far has been in western Europe, the United States and China. In the future, parts of South America and India are expected to produce large amounts of renewable energy. Nuclear power is expected to remain roughly at the same level, and uranium production to remain more or less stable and rather evenly distributed across world regions. Finally, hydropower capacity shows a modest increase under the baseline scenario.

Related IMAGE components
- Atmospheric composition and climate
- Climate policy
- Crops and grass
- Drivers
- Emissions
- Energy conversion
- Energy demand
- Energy supply and demand
- Land cover and land use

Projects/Applications
- ADVANCE project
- Roads from Rio+20 (2012) project

Implemented in computer model
- TIMER model

Key publications
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- Van Vuuren et al., 2008
- Van Vuuren et al., 2009

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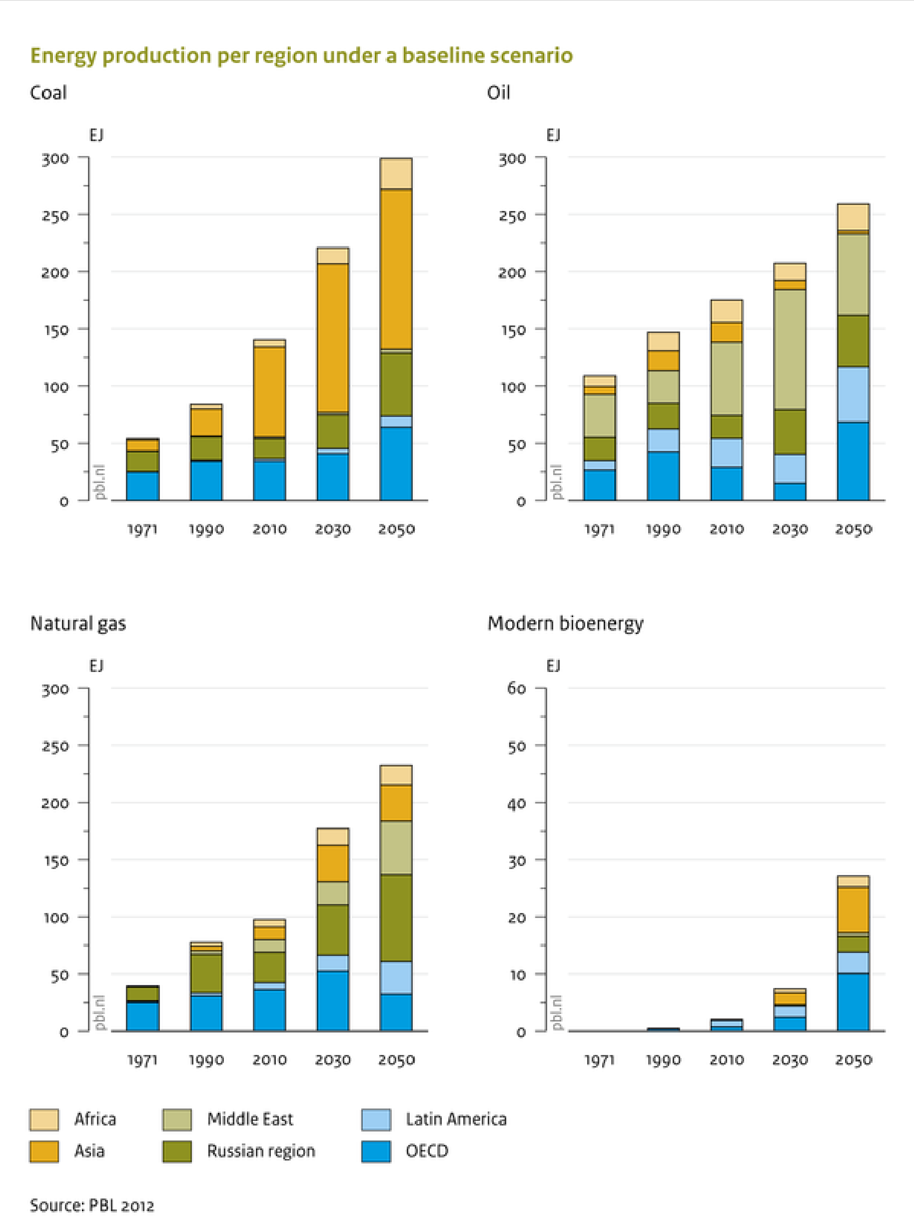


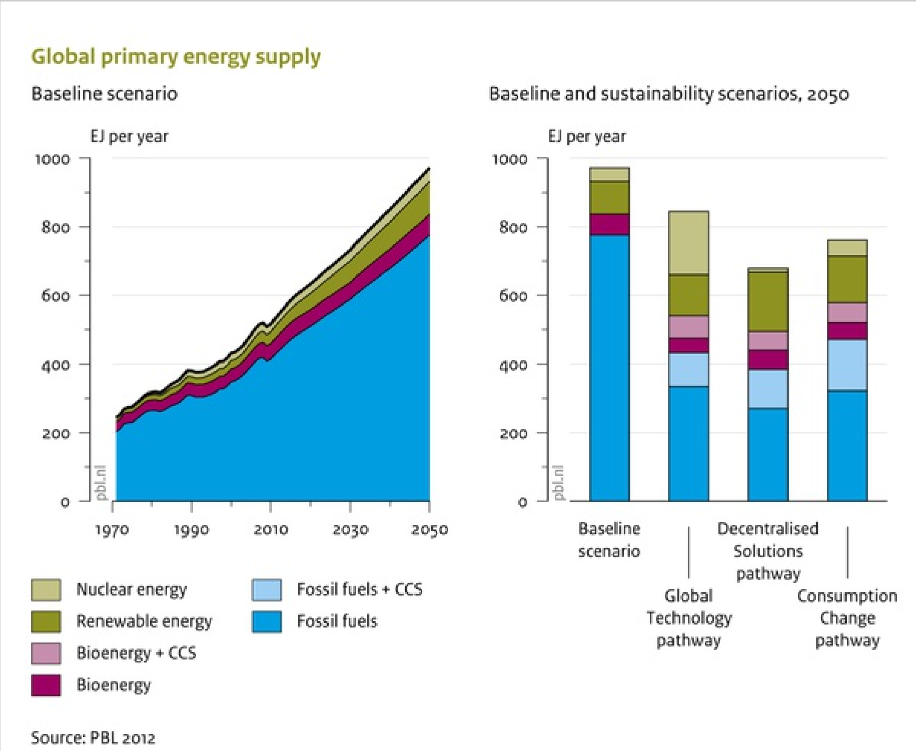
Over time the share of most important energy producers for different forms of energy changes. This has implications for energy security.

Policy interventions

The model can simulate various policies on the supply side:

- Carbon tax. As discussed, a carbon tax can lead to significant changes in the demand for fuels and therefore, also supply.
- Restrictions on fuel trade. As part of energy security policies, fuel trade between different regions can be blocked.
- Sustainability criteria for bioenergy production may restrict production in water-scarce areas.
- Production targets are mostly set to force technologies through a learning curve.

The influence of stringent climate policy on production of primary energy resources is shown in the figure below. Climate policy leads to a major shift from a system mostly based on fossil fuels to an increase in the use of nuclear power, renewable energy, bioenergy and CCS technology, with a correspondingly lower reliance on fossil fuels. The choice of these alternative options depends on assumptions made in the model, as shown in the scenarios in the study Roads from Rio+20 (PBL, 2012). Three pathways based on different initial assumptions emphasise different combinations of primary energy carriers, each time within a stringent emission constraint.



Effects of policy interventions on this component

Policy intervention	Description	Effect
Carbon tax	A tax on carbon leads to higher prices for carbon intensive fuels (such as fossil fuels), making low-carbon alternatives more attractive.	The energy supply will change from the use of carbon intensive energy carriers to the use of low/zero carbon energy carriers.
Change market shares of fuel types	Exogenously set the market shares of certain fuel types. This can be done for specific analyses or scenarios to explore the broader implications of increasing the use of, for instance, biofuels, electricity or hydrogen and reflects the impact of fuel targets. (Reference: Van Ruijven et al., 2007)	A change of the market share of the selected fuel types to the predetermined values.
Implementation of biofuel targets	Policies to enhance the use of biofuels, especially in the transport sector. In the Agricultural economy component only 'first generation' crops are taken into account. The policy is implemented as a budget-neutral policy from government perspective, e.g. a subsidy is implemented to achieve a certain share of biofuels in fuel production and an end-user tax is applied to counterfinance the implemented subsidy. (Reference: Banse et al., 2008)	
Implementation of sustainability criteria in bio-energy production (*)	Sustainability criteria that could become binding for dedicated bio-energy production, such as the restrictive use of water-scarce or degraded areas.	Application of sustainability criteria for bio-energy production, reduces the areas potentially suitable for the cultivation of bio-energy crops, and consequently the marginal costs of bio-energy use ?????? CHECK!!
Improving energy efficiency	Exogenously set improvement in efficiency. Such improvements can be introduced for the submodels that focus on particular technologies, for example, in transport, heavy industry and households submodels.	Efficiency improvements result in a decreased energy demand, resulting in less need for energy supply.
Restrictions on fuel trade (*)	As part of energy security policies, fuel trade between different regions can be blocked.	Less fuel trade will result in a change in fuel prices and availability.

(*) Implemented in this component.

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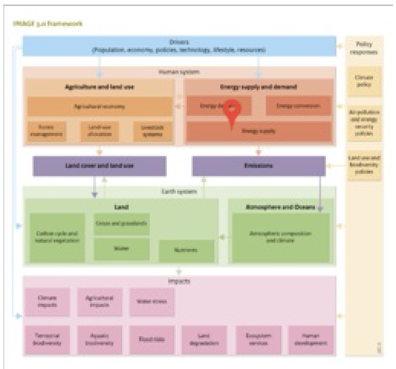

Data, uncertainties and limitation

Data

Main data for the supply side of TIMER are the size of the resources available at different production costs (the table below).

Table: Main data sources for the TIMER energy supply module

Data input	Sources
Fossil-fuel resources and costs	(Mulders et al., 2006). Costs from various sources
Nuclear fuel data (uranium and thorium)	WEC-Uranium (WEC, 2010)
Bioenergy potential and costs	PBL calculations (Van Vuuren et al., 2009; Van Vuuren et al., 2010)
Solar and wind potential	PBL calculations (Hoogwijk, 2004)
CCS potential	Based on (Hendriks et al., 2004b; IPCC, 2005)

Uncertainties

One of the main uncertainties with respect to long-term supply is the size of the resource estimates at various production costs. Estimates of energy resources vary significantly, especially non-conventional resource estimates for oil and natural gas. Equally important uncertainties are the nature and rate of technological advances, and the design and implementation of energy policies in different regions.

Various PBL publications have analysed the sensitivity of the model to supply uncertainties. The Monte Carlo uncertainty analysis of various scenarios (Van Vuuren et al., 2008) identified model parameters as important determinants of the future supply such as oil and natural gas resources and renewable energy learning rates. Some of these factors were only important for a subset of scenario output. For instance, size of oil resources was found to directly influence future oil production, but had limited impact on future CO_2 emissions. The main reason is that oil production in the medium-term is constrained by competition from other fossil fuels and bioenergy. The results were also shown to be scenario dependent. Fossil fuel related uncertainties were more important in a scenario that resulted in a high rather than low fossil-fuel demand.

Limitations

The general limitations of TIMER also apply to energy supply modules with a few specific limitations. As a global model, TIMER specifies resource availability in 26 global regions. However, to some degree this does not take into account the underlying geographical dimensions of individual countries and specific areas. For fossil fuels, this issue leads to heterogeneity within a region (e.g., due to different tax systems), but is more important for renewable energy. A key factor can be transport from one area to another, and calculations require the use of other models.

Another main limitation concerns the focus on production costs in describing energy markets.

Related IMAGE components

- Atmospheric composition and climate
- Climate policy
- Crops and grass
- Drivers
- Emissions
- Energy conversion
- Energy demand
- Energy supply and demand
- Land cover and land use

Projects/Applications

- ADVANCE project
- Roads from Rio+20 (2012) project

Implemented in computer model

- TIMER model

Key publications

- De Vries et al., 2007
- Van Vuuren et al., 2008
- Van Vuuren et al., 2009

References

[Expand]

Although long-term developments may be expected to be driven by long-term supply costs over the last few decades, issues related to capacity constraints and market formation over longer time periods have lead to fossil fuels prices that differ from production costs.

Parts of Energy supply

1. Introduction page
2. Model description
3. Policy issues
4. **Data, uncertainty and limitations**
5. Overview of references

Category: ComponentDataUncertaintyAndLimitations

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Energy supply/References

< Energy supply

Key publications

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Energy conversion

Parts of Energy conversion

1. **Introduction page**
2. Model description
3. Policy issues
4. Data, uncertainty and limitations
5. Overview of references

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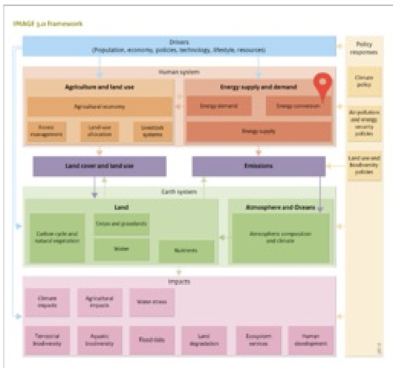


Key policy issues

- What is the potential role of energy conversion sector, particularly in power production, in achieving a more sustainable energy system?
- What are the potential roles of individual technologies, such as carbon capture and storage (CCS), nuclear power, hydrogen and renewable energy?

Introduction

Energy from primary sources often has to be converted into secondary energy carriers that are more easily accessible for final consumption, for example the production of electricity and hydrogen, oil products from crude oil in refineries, and fuels from biomass. Studies on transitions to more sustainable energy systems also show the importance of these conversions for the future.

The energy conversion module of TIMER simulates the choices of input energy carriers in two steps. In the first step, investment decisions are made on the future generation mix in terms of newly added capital. In the second step, the actual use of the capacity in place depends on a set of model rules that determine the purpose and how frequently the different types of power plants are used (baseload/peakload). The discussion focuses on the production of electricity and hydrogen. Other conversion processes have only be implemented in the model by simple multipliers, as they mostly convert energy from a single primary source to one secondary energy carrier. These processes are discussed in Energy supply.

Input/Output Table

Input Energy conversion component

Related IMAGE components

- Energy supply and demand
- Energy demand
- Energy supply
- Land-use allocation
- Climate policy
- Drivers

Projects/Applications

- ADVANCE project
- Roads from Rio+20 (2012) project
- Energy Modelling Forum - EMF

Models/Databases

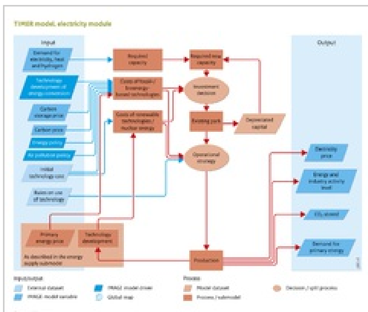
- Enerdata Global Energy & CO2 Data
- IEA database
- WEC-Uranium

Implemented in computer model

- TIMER model

Key publications

- Hoogwijk et al., 2007
- Hendriks et al., 2004a



Flowchart Energy conversion. See also the Input/Output Table on the introduction page.

IMAGE model drivers and variables	Description	Source
Air pollution policy	Air pollution policies set to reach emission reduction targets, represented in the model in the form of energy carrier and sector specific emission factors.	Drivers
Energy policy	Policy to achieve energy system objectives, such as energy security and energy access.	Drivers
Technology development of	Learning curves and exogenous learning that determine technology development.	Drivers

IMAGE model drivers and variables	Description	Source
Carbon price	Carbon price on the international trading market (in USD in 2005 per tonne C-eq) calculated from aggregated regional permit demand and supply curves derived from marginal abatement costs.	Climate policy
Carbon storage price	The costs of capturing and storing CO2, affecting the use of CCS technology.	Energy supply
Demand for electricity, heat and hydrogen	The demand for production of electricity, heat and hydrogen.	Energy demand
Primary energy price	The price of primary energy carriers based on production costs.	Energy supply

External datasets	Description	Source
Initial technology cost	The costs of energy conversion technologies at the start of the simulation..	Various sources
Rules on use of technology	Rules determining how different types of power plants are used.	Various sources

Output Energy conversion component

IMAGE model variables	Description	Use
Electricity price	The price of electricity.	Energy demand
Demand for primary energy	Total demand for energy production. Sum of final energy demand and energy inputs into energy conversion processes.	Energy supply
Energy and industry activity level	Activity levels in the energy and industrial sector, per process and energy carrier, for example, the combustion of petrol for transport or the production of crude oil.	Emissions
CO2 stored	The amount of CO_2 stored in underground reservoirs by applying CO_2 capture technology..	Final output

Category: Component

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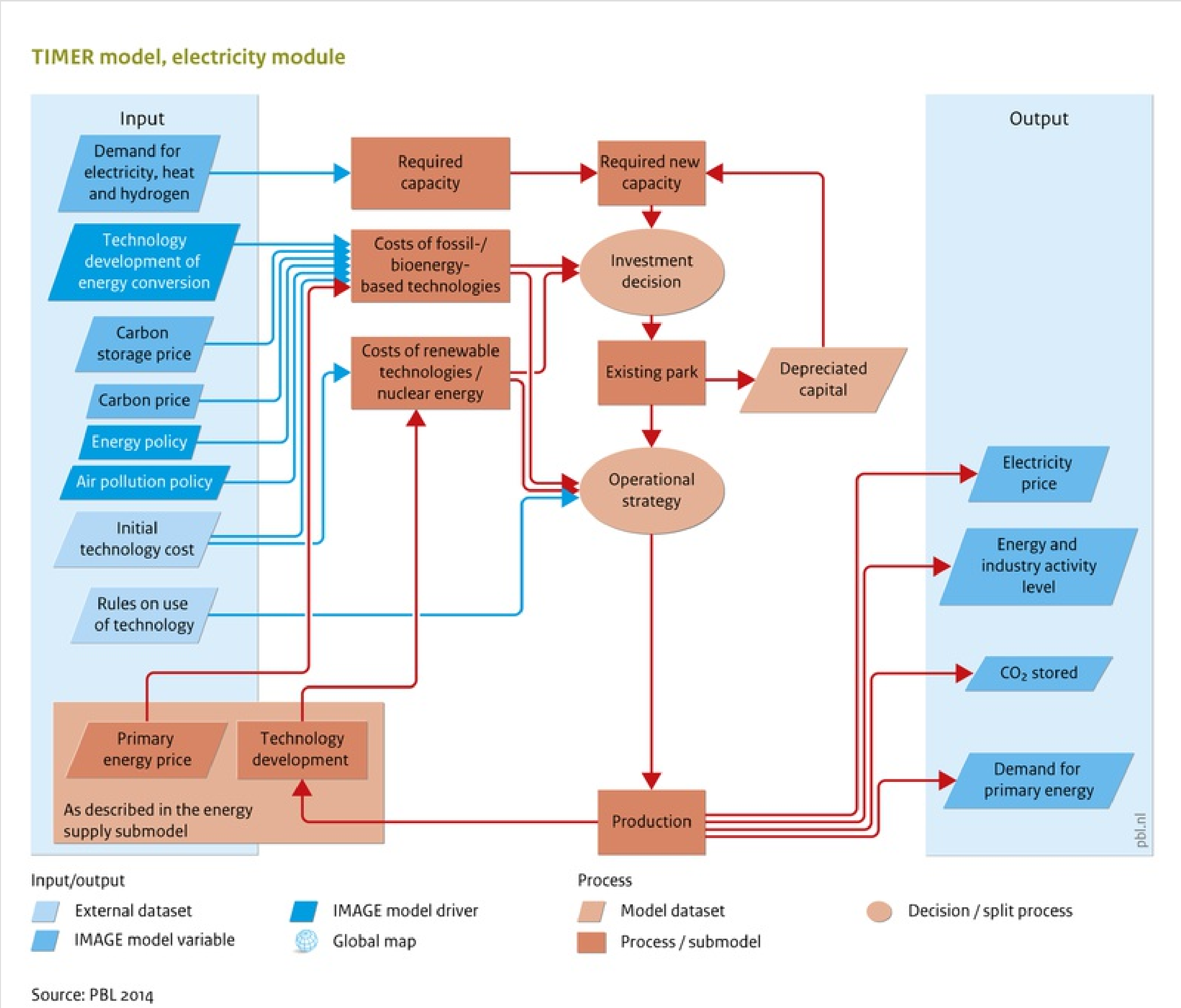
Flowchart Energy conversion



Caption: Flowchart Energy conversion. See also the Input/Output Table on the introduction page.

Figure is used on page(s): Energy conversion

View Image

Category: Figure

Energy conversion/Description

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Additional info

6. Carbon capture and storage
7. Technical learning
8. Grid and infrastructure

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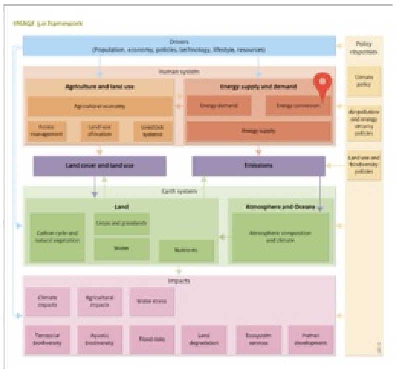

Model description of Energy conversion

TIMER includes two main energy conversion modules: Electric power generation and hydrogen generation. Below, electric power generation is described in detail. In addition, the key characteristics of the hydrogen generation model, which follows a similar structure, are presented.

Electric power generation

As shown in the flowchart, two key elements of the electric power generation are the investment strategy and the operational strategy in the sector. A challenge in simulating electricity production in an aggregated model is that in reality electricity production depends on a range of complex factors, related to costs, reliance, and the time required to switch on technologies. Modelling these factors requires a high level of detail and thus IAMs) such as TIMER concentrate on introducing a set of simplified, meta relationships (Hoogwijk, 2004; Van Vuuren, 2007).

Total demand for new capacity

The electricity capacity required to meet the demand per region is based on a forecast of the maximum electricity demand plus a reserve margin of about 10% (including the capacity credit assigned to different forms of electricity generation). Maximum demand is calculated on the basis of an assumed monthly shape of the load duration curve (LDC) and the gross electricity demand. The latter comprises the net electricity demand from the end-use sectors plus electricity trade and transmission losses (LDC accounts for characteristics such as cooling and lighting demand). The demand for new generation capacity is the difference between the required and existing capacity. Power plants are assumed to be replaced at the end of their lifetime, which varies from 30 to 50 years, depending on the technology and is currently fixed in the model.

Decisions to invest in specific options

In the model, the decision to invest in generation technologies is based on the price of electricity (in USD/kWhe) produced per technology, using a multinomial logit equation that assigns larger market shares to the lower cost options. The specific cost of each option is broken down into several categories: investment or capital cost (USD/kWe); fuel cost (USD/GJ); operational and maintenance costs (O&M); and other costs (see further). The exception is hydropower capacity, which is exogenously prescribed, because large hydropower plants often have additional functions such as water supply and flood control. In the equations, some constraints are added to account for limitations in supply, for example restrictions on biomass availability. The investment for each option is given as the total investment in new generation capacity and the share of each individual technology determined on the basis of price and preference.

Operational strategy

Use of power plants is based on operational costs, with low-cost technologies assumed to be used most often. This implies that capital-intensive plants with low operational costs, such as renewable and nuclear energy, operate as many hours as possible. To some degree, this is also true for other plants with low operational costs, such as coal. The operational decision is presented in the following three steps:

1. Renewable sources PV and wind are assigned, followed by hydropower, because these options have

Related IMAGE components

- Climate policy
- Drivers
- Energy demand
- Energy supply
- Energy supply and demand
- Land-use allocation

Projects/Applications

- ADVANCE project
- Energy Modelling Forum - EMF
- Roads from Rio+20 (2012) project

Models/Databases

- Enerdata Global Energy & CO2 Data
- IEA database
- WEC-Uranium

Implemented in computer model

- TIMER model

Key publications

- Hendriks et al., 2004a
- Hoogwijk et al., 2007

References

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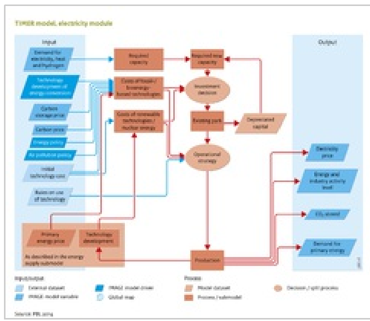

Flowchart Energy conversion. See also the Input/Output Table on the introduction page.

the lowest operational costs;

2. The peak load capacity (period of high electricity demand) is assigned on the basis of the operational costs of each available plant and the ability of these plants to provide peak load capacity;
3. Base load (period of medium to low energy demand) is assigned on the basis of the remaining capacity (after steps 1 and 2), operational costs and the ability of options to provide the base load capacity.

Fossil-fuel and bio-energy power plants

A total of 20 types of power plants generating electricity using fossil fuels and bioenergy are included. These power plants represent different combinations of conventional technology, such as gasification and combined cycle (CC) technology; combined heat and power (CHP); and carbon capture and storage (CCS)(Hendriks et al., 2004b). The specific capital costs and thermal efficiencies of these types of plants are determined by exogenous assumptions that describe the technological progress of typical components of these plants:

- For conventional power plants, the coal-fired plant is defined in terms of overall efficiency and investment cost. The characteristics of all other conventional plants (using oil, natural gas or bioenergy) are described in the investment differences for desulphurisation, fuel handling and efficiency.
- For Combined Cycle (CC) power plants, the characteristics of a natural gas fired plant are set as the standard. Other CC plants (fuelled by oil, bioenergy and coal after gasification) are defined by indicating additional capital costs for gasification, efficiency losses due to gasification, and operation and maintenance (O&M) costs for fuel handling.
- Power plants with carbon-capture-and-storage systems (CCS) are assumed to be CC plants, but with fuel-specific lower efficiency and higher investment and O&M costs (related to capture and storage).
- The characteristics of combined-heat-and-power plants (CHP) are similar to those of other plants, but with an assumed small increase in capital costs, in combination with a lower efficiency for electric conversion and an added factor for heat efficiency.

The cost of one unit electricity generated is equal to the sum of the capital cost, operational and maintenance costs (O&M), fuel cost, and CO_2 storage cost.

See the additional info on Grid and infrastructure and Carbon capture and storage.

Solar and wind power

The costs of solar and wind power in the model are determined by learning and depletion dynamics. For renewable energy, costs relate to capital, O&M and system integration. The capital costs mostly relate to learning and depletion processes. Learning is represented by in learning curves (see Page on Technical learning); depletion is by long-term in cost–supply curves.

The additional system integration costs relate to curtailed electricity (if production exceeds demand and the overcapacity cannot be used within the system), backup capacity; and additional required spinning reserve. The last items are needed to avoid loss of power if the supply of wind or solar power drops suddenly, enabling a power scale up in a relatively short time, in power stations operating below maximum capacity (Hoogwijk, 2004).

To determine curtailed electricity, the model compares 10 points on the load-demand curve at the overlap between demand and supply. For both wind and solar power, a typical load supply curve is assumed (see Hoogwijk, 2004). If supply exceeds demand, the overcapacity in electricity is assumed to be discarded, resulting in higher production costs.

Because wind and solar power supply is intermittent (variable and thus not reliable), the model assumes that backup capacity needs to be installed. It is assumed that no backup is required for first 5% penetration of the intermittent capacity. However, for higher levels of penetration, the effective capacity (degree to which operators can rely on plants producing at a specific time) of intermittent resources is assumed to decrease. This is referred to as the capacity factor. This decrease leads to the need for backup power by low-cost options, such as gas turbines, the cost of which is allocated to the intermittent source.

The required spinning reserve of the power system is the capacity that can be used to respond to a rapid increase in demand. This is assumed to be 3.5% of the installed capacity of a conventional power plant. If wind and solar power further penetrate the market, the model assumes an additional, required spinning reserve of 15% of the intermittent capacity (after subtraction of the 3.5% existing capacity). The related costs are allocated to the intermittent source.

Nuclear power

The costs of nuclear power also include capital, O&M and nuclear fuel costs. Similar to the renewable energy options, technology improvement in nuclear power is described via a learning curve (costs decrease with cumulative installed capacity). Fuel costs increase as a function of depletion. Fuel costs are determined on the basis of the estimated extraction costs for uranium and thorium resources, see Energy supply. A small trade model for these fission fuels is included..

Hydrogen generation

The structure of the hydrogen generation submodule is similar to that for electric power generation (Van Ruijven et al., 2007) but with following differences:

1. There are only eleven supply options for hydrogen production:
    - coal, oil, natural gas and bioenergy, with and without carbon capture and storage (8 plants);
    - hydrogen production from electrolysis, direct hydrogen production from solar thermal processes;

- small methane reform plants.

2. No description of preferences for different power plants is taken into account in the operational strategy. The load factor for each option equals the total production divided by the capacity for each region.
3. Intermittence does not play an important role because hydrogen can be stored to some degree. Thus, there are no equations simulating system integration.
4. Hydrogen can be traded. A trade model is added, similar to those for fossil fuels described in Energy supply.

See the additional info on Grid and infrastructure.

Parts of Energy conversion

Energy conversion/Policy issues

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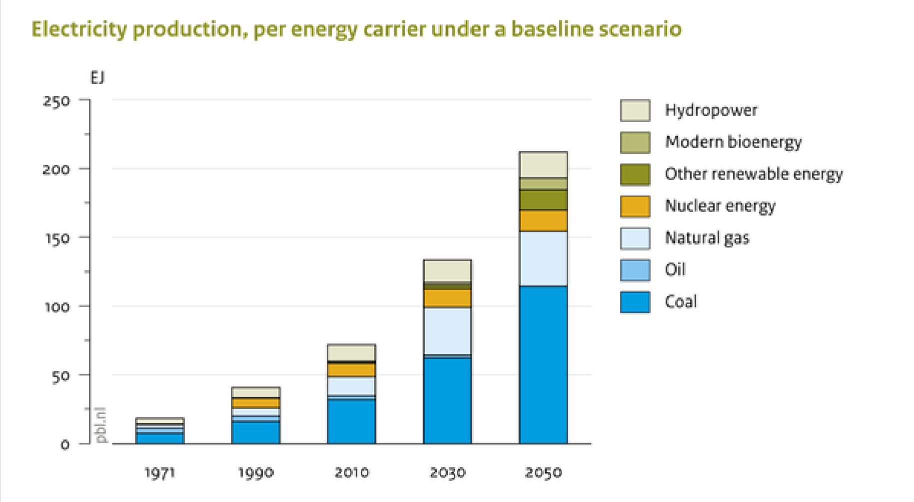
Baseline developments

The energy conversion module may be used to generate scenarios with and without climate policy. The results for a typical baseline scenario are shown in the figure below. At present, coal is the main feedstock for power generation globally. In high-income regions, coal faces competition from natural gas, but in emerging economies, such as China and India, coal is still by far the largest resource used. The baseline scenario projects coal use to expand. The underlying reasons for this expansion are the rapid increase in electricity use in emerging economies, and the stronger price increases for natural gas than for coal. The latter, clearly, also depends on the uncertainty in future natural gas supply. On a global scale, wind power and biomass-fired power plants are rapidly expanding in total capacity.



Increase in primary energy demand for electricity production is dominated by coal, despite a rapid growth of renewable energy.

Policy interventions

IMAGE model simulations include several types of policy interventions that may influence electricity and hydrogen production:

- Carbon tax: this measure is usually implemented on an economy-wide scale and has strong influence on investment and operational strategies in the power system. Because prices are relatively low, there are several competitive power alternatives, and power system choices are usually rather objectively.
- An imposed minimum or maximum share per energy source - renewable energy, CCS technology, nuclear power and other forms of power generation. This would directly influence the capacity installed for each option.

Related IMAGE components
- Climate policy
- Drivers
- Energy demand
- Energy supply
- Energy supply and demand
- Land-use allocation

Projects/Applications
- ADVANCE project
- Energy Modelling Forum - EMF
- Roads from Rio+20 (2012) project

Models/Databases
- Enerdata Global Energy & CO2 Data
- IEA database
- WEC-Uranium

Implemented in computer model
- TIMER model

Key publications
- Hendriks et al., 2004a
- Hoogwijk et al., 2007

References

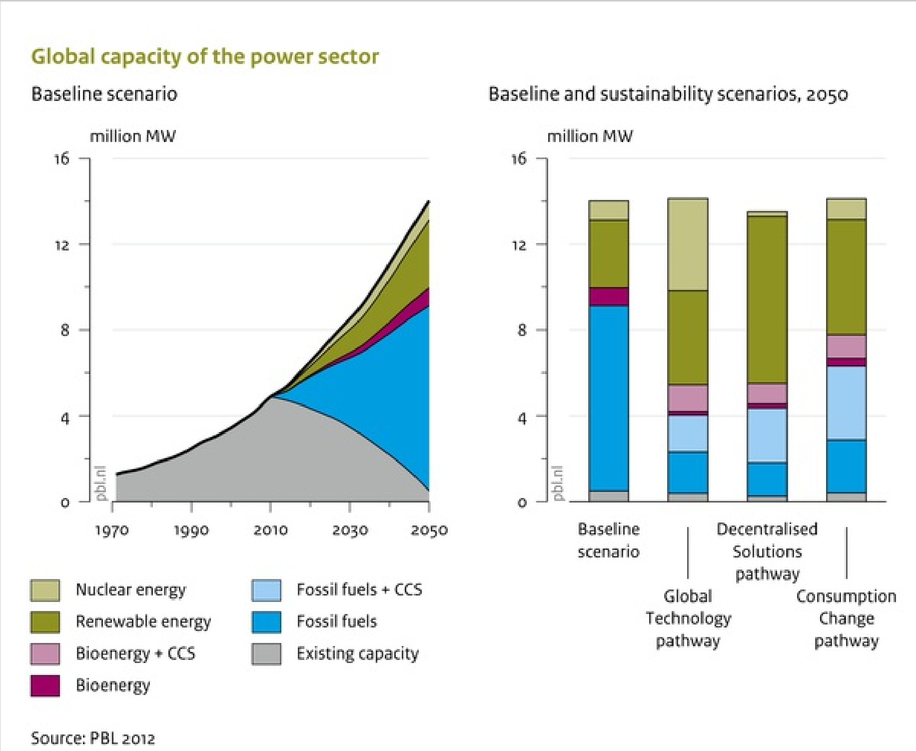
[Expand]

- Promoting the use of electricity and hydrogen on end-user level. With the high flexibility in the choice of feedstock in these systems, large proportions of electricity and hydrogen use in final energy would increase the ability of the total system to reduce greenhouse gas emissions.

The exclusion of certain power-generation options for environmental and/or security reasons (Kruyt et al., 2009).

Model analyses show that a high proportion of emission reductions would be achieved through supply side changes. The capacity for different supply-side options under the baseline scenario and various pathways consistent with the 2 °C climate change target are presented in the figure below.

The proportion of unabated fossil fuel use is still 80% of total primary energy under the baseline scenario (see above) but by 2050, this would need to be around 15 to 20% according to the 2 °C scenarios. The results show that pathways can be identified in which the remaining energy comes from bioenergy, other renewable energy, nuclear energy, and from fossil-fuel energy combined with CCS. There is flexibility in the choice of these options, as illustrated in the Decentralised Solutions and Global Technology pathways with different patterns for nuclear power and renewable energy. In the IMAGE framework under nearly all scenarios, the combination of bioenergy and CCS, and CCS in general, plays a critical role in achieving the 2 °C target.



The large share of conventional coal power in the baseline is replaced by fossil power with CCS and renewable capacity in the sustainability scenarios.

Effects of policy interventions on this component

Policy intervention	Description	Effect
Capacity targets (*)	It is possible to prescribe the shares of renewables, CCS technology, nuclear power and other forms of generation capacity. This measure influences the amount of capacity installed of the technology chosen.	Manually changing the generation capacity will result in a transition towards using more or less capacity of the selected generation type.
Carbon tax (*)	A tax on carbon leads to higher prices for carbon intensive fuels (such as fossil fuels), making low-carbon alternatives more attractive.	A carbon tax will induce a transition from carbon intensive fuel to carbon low fuels. Since hydrogen and electricity are well suited for carrying carbon low energy, the production of hydrogen and electricity could increase.
Change market shares of fuel types	Exogenously set the market shares of certain fuel types. This can be done for specific analyses or scenarios to explore the broader implications of increasing the use of, for instance, biofuels, electricity or hydrogen and reflects the impact of fuel targets. (Reference: Van Ruijven et al., 2007)	An interference with the share of fuel types, results in a change of the market share of the selected fuel types to the predetermined values. This again results in less conversion capacity of the selected fuel type.
Change the use of electricity and hydrogen (*)	It is possible to promote the use of electricity and hydrogen at the end-use level.	This policy intervention will result in more hydrogen or electricity production and generation capacity.
Excluding certain technologies (*)	Certain energy technology options can be excluded in the model for environmental, societal, and/or security reasons. (Reference: Kruyt et al., 2009)	This policy intervention will result in the exclusion of the selected technologies. This is likely to result in an increased use of alternative technologies.
Improving energy efficiency	Exogenously set improvement in efficiency. Such improvements can be introduced for the submodels that focus on particular technologies, for example, in transport, heavy industry and households submodels.	Efficiency improvements result in less energy input at an equal energy output of conversion technologies. This results in a lower need for conversion capacity.

Policy intervention	Description	Effect
Production targets for energy technologies	Production targets for energy technologies can be set to force technologies through a learning curve.	Production targets force a conversion technology to convert energy, even though this is not economically attractive. If the learning rate of that technology depends on the amount of converted energy, the learning rate will increase.
Restrictions on fuel trade	As part of energy security policies, fuel trade between different regions can be blocked.	Less fuel trade will result in a change in fuel prices and availability. As a result, the amount of conversion capacity can increase or decrease.

(*) Implemented in this component.

Parts of Energy conversion

Category: ComponentPolicyIssue

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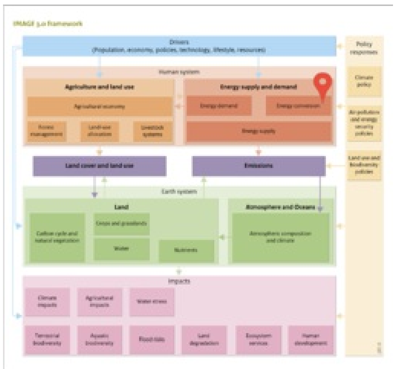

Data, uncertainties and limitations

Data

The data for the model come from a variety of sources, the main of which are:

Table: Main data sources for the TIMER energy conversion module

Input	Data source
Electricity production and primary inputs	IEA Statistics and Data
Capacity of different plant types per region	Energy Statistics and Data (Enerdata Global Energy & CO2 Data; IEA Statistics and Data)
Performance of fossil fuel and bio-energy fired plants	Hendriks et al. (2004a)
CCS plants and storage	Hendriks et al. (2004b)
Prices	IEA Statistics and Data
Hydropower potential	World Energy Council (WEC, 2010)
Solar and wind costs	Hoogwijk et al., 2007
Nuclear power - technology and resources	WEC-Uranium (WEC, 2010; MIT, 2003)
Hydrogen technologies	Van Ruijven et al., 2007

Uncertainties

The two main uncertainties are calculation of future energy conversion relating to development rates of the conversion technologies, and the consequences for the electricity system of a high level of market penetration of renewable energy. TIMER electric power generation submodule has been tested for different levels of market penetration of renewable energy in the United States and western Europe (Hoogwijk et al., 2007). The model was shown to reproduce the behaviour of more detailed models that describe system integration costs. More recent studies seem to suggest that some of the limitations in renewable energy penetration can be overcome at reasonable costs, implying the current description is rather conservative. Integration costs for renewable energy are very uncertain because large shares of market penetration still need to be achieved, except in a few countries. In experiments run by The power system was exposed to all types of technology limitations in experiments run by Van Vliet et al. (2013). These experiments showed that to achieve low stabilisation targets, a large portfolio of mitigation options should be available.

Limitations

The model describes long-term trends in the energy system, which implies that the focus is on aggregated factors that may determine future energy demand and supply. However in energy conversion, many short-term dynamics can be critical for the system, such as system reliability and ability to respond to demand fluctuations. These processes can only be represented in an

Related IMAGE components

- Climate policy
- Drivers
- Energy demand
- Energy supply
- Energy supply and demand
- Land-use allocation

Projects/Applications

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Models/Databases

- Enerdata Global Energy & CO2 Data
- IEA database
- WEC-Uranium

Implemented in computer model

- TIMER model

Key publications

- Hendriks et al., 2004a
- Hoogwijk et al., 2007

References

[Expand]

aggregated global model in terms of meta-formulations, which implies that some of the integration issues regarding renewable energy are still not addressed.

Another limitation is the formulation of primary fossil-fuel conversions in secondary fuels. TIMER currently does not include a module that explicitly describes these processes.

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Key publications

Hendriks et al., 2004a

C. Hendriks, M Harmelink, K. Burges, K. Ransel (2004). Power and heat productions: plant developments and grid losses, Ecofys, Utrecht.

Hoogwijk et al., 2007

M. Hoogwijk, D. van Vuuren, B. de Vries, W. Turkenburg (2007). Exploring the impact on cost and electricity production of high penetration levels of intermittent electricity in OECD Europe and the USA, results for wind energy. Energy, 32(8), pp.1381-1402.
Link to PBL-website:
http://www.pbl.nl/en/publications/2007/Exploringtheimpactoncostandelectricityproductionofhighpenetrationlevelsofintermittentelectricityin.

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Category: AllReferencesPages

Emissions

Parts of Emissions

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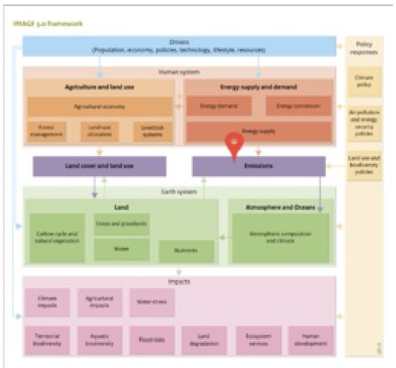


Projects/Applications

- Roads from Rio+20 (2012) project

Key publications

- Van Vuuren et al., 2006
- Braspenning Radu et al., submitted
- Van Vuuren et al., 2011b

Key policy issues

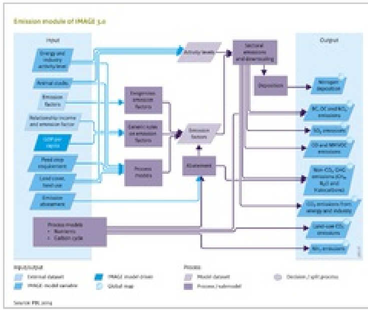
- How will emissions of greenhouse gases and air pollutants develop in scenarios with and without policy interventions, such as climate policy and air pollution control?
- What synergies between climate policy and air pollution control can be identified?

Introduction

Emissions of greenhouse gases and air pollutants are major contributors to environmental impacts, such as climate change, acidification, eutrophication, urban air pollution and water pollution. These emissions stem from anthropogenic and natural sources. Anthropogenic sources include energy production and consumption, industrial processes, agriculture and land-use change, while natural sources include wetlands, oceans and unmanaged land. Better understanding the drivers of these emissions and the impact of abatement measures is needed in developing policy interventions to reduce long-term environmental impacts.

Input/Output Table

Input Emissions component



Flowchart Emissions. See also the Input/Output Table on the introduction page. Anthropogenic sources, for natural sources see Table 5.2.2. More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Emission table).

IMAGE model drivers and variables	Description	Source
GDP per capita	Gross Domestic Product per capita, measured as the market value of all goods and services produced in a region in a year, and is used in the IMAGE framework as a generic indicator of economic activity.	Drivers
Animal stocks	Number of animals per category: non-dairy cattle; dairy cattle; pigs; sheep and goats; poultry.	Livestock systems
Emission abatement	Reduction in emission factors as a function of Climate policy.	Climate policy
Energy and industry activity level	Activity levels in the energy and industrial sector, per process and energy carrier, for example, the combustion of petrol for transport or the production of crude oil.	Energy conversion, Energy supply, Energy demand
Feed crop requirement	Total amount of feed required for the production of animal products. Grass and fodder species are consumed by grazing animals only (dairy and non-dairy cattle, sheep and goats), while pigs and poultry are fed feed crops and other feedstuffs.	Livestock systems
Land cover, land use - grid	Multi-dimensional map describing all aspects of land cover and land use per grid cell, such as type of natural vegetation, crop and grass fraction, crop management, fertiliser and manure input, livestock density.	Land cover and land use

External datasets	Description	Source

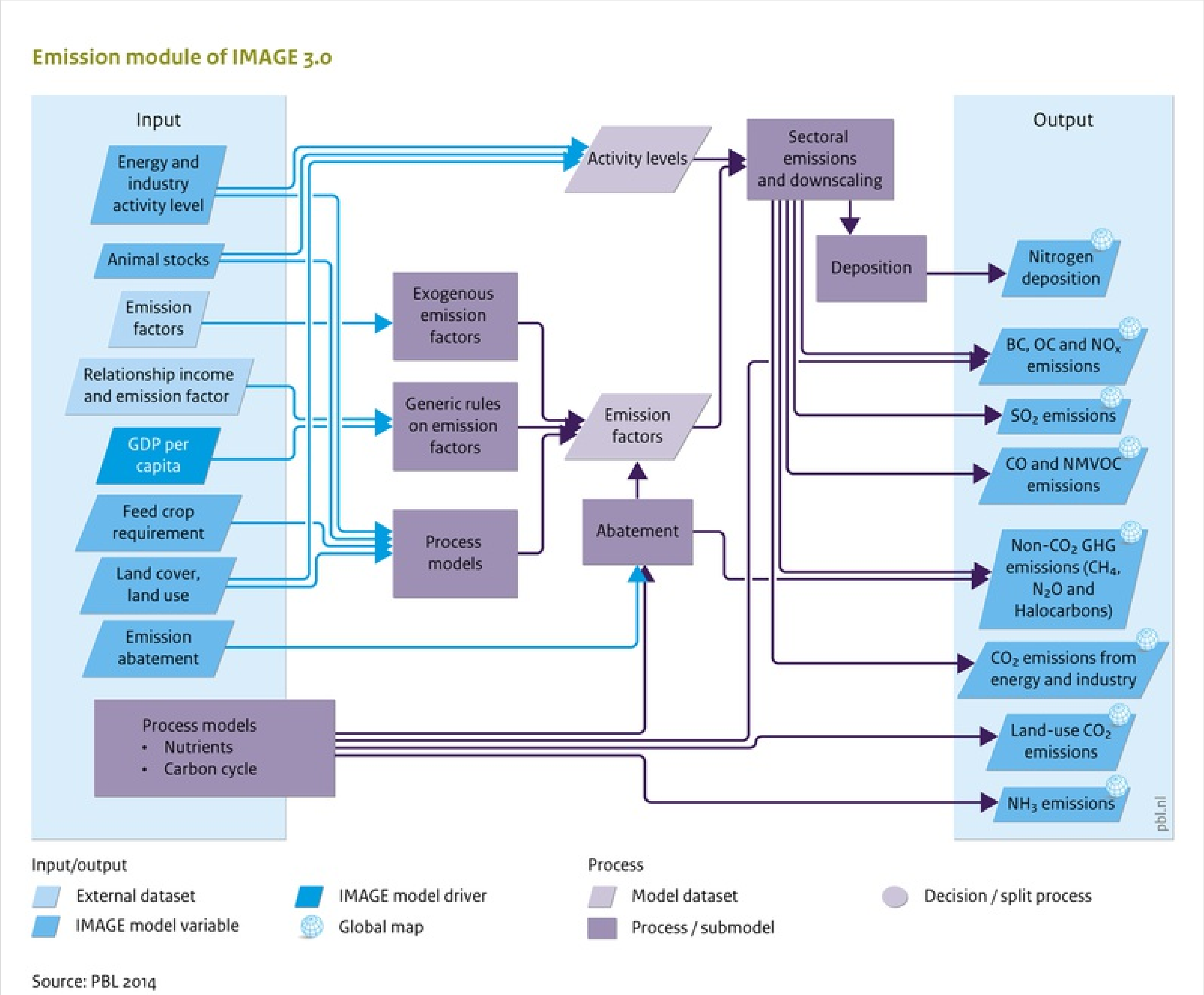
External datasets	Description	Source
Emission factors	Exogenous emission factors per sector, activity and gas, mostly based on the EDGAR database.	EDGAR database
Relationship income and emission factor	Relationship between GDP and emission factors.	

Output Emissions component

IMAGE model variables	Description	Use
Nitrogen deposition - grid	Deposition of nitrogen.	Nutrients; Terrestrial biodiversity
CO and NMVOC emissions	Emissions from CO and NMVOC.	Atmospheric composition and climate; Climate policy
CO2 emission from energy and industry	CO_2 emission from energy and industry.	Atmospheric composition and climate; Climate policy
Non-CO2 GHG emissions (CH4, N2O and Halocarbons)	Non-CO_2 GHG emissions (CH_4, N_2O, Halocarbons).	Atmospheric composition and climate; Climate policy
BC, OC and NOx emissions	Emissions of BC, OC and NO_x per year.	Atmospheric composition and climate; Climate policy; Human development
SO2 emissions	SO_2 emissions, per source (e.g. fossil fuel burning, deforestation).	Atmospheric composition and climate; Climate policy; Human development

Parts of Emissions

Flowchart Emissions



Caption: Flowchart Emissions. See also the Input/Output Table on the introduction page. Anthropogenic sources, for natural sources see Table 5.2.2. More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Emission table).

Figure is used on page(s): Emissions

View Image

Category: Figure

Emissions/Description

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Parts of Emissions

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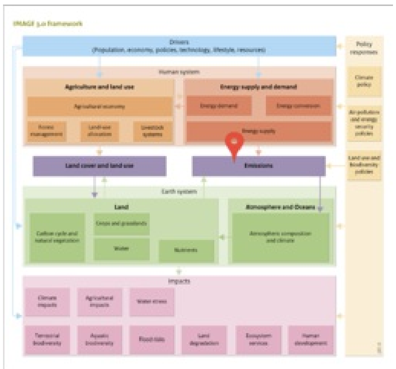

Projects/Applications

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Key publications

- Braspenning Radu et al., submitted
- Van Vuuren et al., 2006
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References

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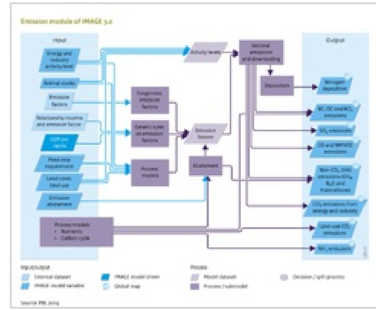

Flowchart Emissions. See also the Input/Output Table on the introduction page. Anthropogenic sources, for natural sources see Table 5.2.2. More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Emission table).

Model description of Emissions

General approaches

Air pollution emission sources included in IMAGE are listed in Emission table, and emissions transported in water (nitrate, phosphorus) are discussed in Component Nutrients. In approach and spatial detail, gaseous emissions are represented in IMAGE in four ways:

1) *World number (W)*

The simplest way to estimate emissions in IMAGE is to use global estimates from the literature. This approach is used for natural sources that cannot be modelled explicitly (Emission table).

2) *Emission factor (EF)*

Past and future developments in anthropogenic emissions are estimated on the basis of projected changes in activity and emissions per unit of activity (Figure Flowchart).

The equation for this emission factor approach is:

$$\text{Emission} = \text{Activity}_{r,i} * \text{EF-base}_{r,i} * \text{AF}_{r,i} \quad \text{(Equation 1)}$$

where:

- Emission is the emission of the specific gas or aerosol;
- Activity is the energy input or agricultural activity; r is the index for region;
- i is the index for further specification (sector, energy carrier);
- EF-base is the emission factor in the baseline;
- AF is the abatement factor (reduction in the baseline emission factor as a result of climate policy).

The emission factors are time-dependent, representing changes in technology and air pollution control and climate mitigation policies.

The emission factor is used to calculate energy and industry emissions, and agriculture, waste and land-use related emissions. Following Equation 1, there is a direct relationship between level of economic activity and emission level. Shifts in economic activity (e.g., use of natural gas instead of coal) may influence total emissions. Finally, emissions can change as a result of changes in emission factors (EF) and climate policy (AF).
Some generic rules are used in describing changes in emissions over time (see further). The abatement factor (AF) is determined in the climate policy model FAIR (see Component Climate policy). The emission factor approach has some limitations, the most important of which is capturing the consequences of specific emission control technology (or management action) for multiple gas species, either synergies or trade-offs.

3) *Gridded emission factor with spatial distribution (GEF)*

GEF is a special case of the EF method, where a proxy distribution is used to present gridded emissions. This is done for a number of sources, such as emissions from livestock (Emission table).

4) *Gridded process model (GPM)*

Land-use related emissions of NH_3, N_2O and NO are calculated with grid-specific models (Figure

Flowchart). The models included in IMAGE are simple regression models that generate an emission factor (Figure Flowchart). For comparison with other models, IMAGE also includes the N_2O methodology generally proposed by IPCC (IPCC, 2006).

The approaches used to calculate emissions from energy production and use, industrial processes and land-use related sources are discussed in more detail below.

Emissions from energy production and use

Emission factors (Equation 1) are used for estimating emissions from the energy-related sources (Emission table). In general, the Tier 1 approach from IPCC guidelines (IPCC, 2006) is used. In the energy system, emissions are calculated by multiplying energy use fluxes by time-dependent emission factors. Changes in emission factors represent, for example, technology improvements and end-of-pipe control techniques, fuel emission standards for transport, and clean-coal technologies in industry.

The emission factors for the historical period for the energy system and industrial processes are calibrated with the EDGAR emission model described by Braspenning Radu et al. (in preparation). Calibration to the EDGAR database is not always straightforward because of differences in aggregation level. The general rule is to use weighted average emission factors for aggregation. However, where this results in incomprehensible emission factors (in particular, large differences between the emission factors for the underlying technologies), specific emission factors were chosen.

Future emission factors are based on the following rules:

- Emission factors can follow an exogenous scenario, which can be based on the storyline of the scenario. In some cases, exogenous emission factor scenarios are used, such as the Current Legislation Scenario (CLE) developed by IIASA (for instance, Cofala et al., (2002). The CLE scenario describes the policies in different regions for the 2000–2030 period.
- Alternatively, emission factors can be derived from generic rules, one of which in IMAGE is the EKC: Environmental Kuznets Curve (Stern, 2003; Smith et al., 2005; Van Ruijven et al., 2008; Carson, 2010; Smith et al., 2011). EKC suggests that starting from low-income levels, per-capita emissions will increase with increasing per-capita income and will peak at some point and then decline. The last is driven by increasingly stringent environmental policies, and by shifts within sectors to industries with lower emissions and improved technology. Although such shifts do not necessarily lead to lower absolute emissions, average emissions per unit of energy use decline. See below, for further discussion of EKC.
- Combinations of the methods described above for a specific period, followed by additional rules based on income levels.

In IMAGE, EKC is used as an empirically observed trend, as it offers a coherent framework to describe overall trends in emissions in an Integrated Assessment context. However , it is accepted that many driving forces other than income influence future emissions. For instance, more densely populated regions are likely to have more stringent air quality standards. Moreover, technologies developed in high-income regions often tend to spread within a few years to developing regions. The generic equations in IMAGE can capture this by decreasing the threshold values over time. For CO_2 and other greenhouse gases, such as halogenated gases for which there is no evidence of EKC behaviour, IMAGE uses an explicit description of fuel use and deforestation.

The methodology for EKC scenario development applied in the energy model is based on two types of variables: income thresholds (2–3 steps); and gas- and sector-dependent reduction targets for these income levels. The income thresholds are set to historical points: the average OECD income at which air pollution control policies were introduced in these countries; and current income level in OECD countries. The model assumes that emission factors will start to decline in developing countries, when they reach the first income threshold, reflecting more efficient and cleaner technology. It also assumes that when developing countries reach the second income threshold, the emission factors will be equal to the average level in OECD regions. Beyond this income level, the model assumes further reductions, slowly converging to the minimum emission factor in OECD regions by 2030, according to projections made by IIASA under current legislation (current abatement plans). The IMAGE rules act at the level of regions, this could be seen as a limitation, but as international agreements lead countries to act as a group, this may not be an important limitation.

Emissions from industrial processes

For the industry sector, the energy model includes three categories:

1. Cement and steel production. IMAGE-TIMER includes detailed demand models for these commodities (Component Energy supply and demand). Similar to those from energy use, emissions are calculated by multiplying the activity levels to exogenously set emission factors.
2. Other industrial activities. Activity levels are formulated as a regional function of industry value added, and include copper production and production of solvents. Emissions are also calculated by multiplying the activity levels by the emission factors.
3. For halogenated gases, the approach used was developed by Harnisch et al. (2009), which derived relationships with income for the main uses of halogenated gases (HFCs, PFCs, SF_6). In the actual use of the model, slightly updated parameters are used to better represent the projections as presented by Velders et al. (2009). The marginal abatement cost curve per gas still follows the methodology described by Harnisch et al. (2009).

Land-use related emissions

CO_2 exchanges between terrestrial ecosystems and the atmosphere computed by the LPJ model are described in Carbon cycle and natural vegetation. The land-use emissions model focuses on emissions of other compounds, including greenhouse gases (CH_4, N_2O), ozone precursors (NO_x, CO, NMVOC), acidifying compounds (SO_2, NH_3) and aerosols (SO_2, NO_3, BC, OC).

For many sources, the emission factor (Equation 1) is used (Emission table). Most emission factors for anthropogenic sources are from the EDGAR database, with time-dependent values for historical years. In the scenario period, most emission factors are constant, except for explicit climate abatement policies (see below).

There are some other exceptions: Various land-use related gaseous nitrogen emissions are modelled in grid-specific models (see further), and in several other cases, emission factors depend on the assumptions described in other parts of IMAGE. For example, enteric fermentation CH_4 emissions from non-dairy and dairy cattle are calculated on the basis of energy requirement and feed type (see Component Livestock systems). High-quality feed, such as concentrates from feed crops, have a lower CH_4 emission factor than feed with a lower protein level and a higher content of components of lower digestibility. This implies that when feed conversion ratios change, the level of CH_4 emissions will automatically change. Pigs, and sheep and goats have IPCC 2006 emission factors, which depend on the level of development of the countries. In IMAGE, agricultural productivity is used as a proxy for the development. For sheep and goats, the level of development is taken from EDGAR.

Constant emission factors may lead to decreasing emissions per unit of product, for example, when the emission factor is specified on a per-head basis. An increasing production per head may lead to a decrease in emissions per unit of product. For example, the CH_4 emission level for animal waste is a constant per animal, which leads to a decrease in emissions per unit of meat or milk when production per animal increases.

A special case is N_2O emissions after forest clearing. After deforestation, litter remaining on the soil surface as well as root material and soil organic matter decompose in the first years after clearing, which may lead to pulses of N_2O emissions. To mimic this effect, emissions in the first year after clearing are assumed to be five times the flux in the original ecosystem. Emissions decrease linearly to the level of the new ecosystem in the tenth year, usually below the flux in the original forest. For more details, see Kreileman and Bouwman (1994).

Land-use related emissions of NH_3, N_2O and NO are calculated withgrid-specific models.N_2O from soils under natural vegetation is calculated with the model developed by Bouwman et al. (1993). This regression model is based on temperature, a proxy for soil carbon input, soil water and oxygen status, and for net primary production. Ammonia emissions from natural vegetation are calculated from net primary production, C:N ratio and an emission factor. The model accounts for in-canopy retention of the emitted NH_3 (Bouwman et al., 1997).

For N_2O emissions from agriculture, the determining factors in IMAGE are N application rate, climate type, soil organic carbon content, soil texture, drainage, soil pH, crop type, and fertiliser type. The main factors used to calculate NO emissions include N application rate per fertiliser type, and soil organic carbon content and soil drainage (for detailed description, see Bouwman et al. (2002a). For NH_3 emissions from fertilised cropland and grassland, the factors used in IMAGE are crop type, fertiliser application rate per type and application mode, temperature, soil pH, and CEC (Bouwman et al., 2002a).

For comparison with other models, IMAGE also includes the N_2O methodology proposed by IPCC (2006). This methodology represents only anthropogenic emissions. For emissions from fertilizer fields this is the emission from a fertilized plot minus that from a control plot with zero fertilizer application. For this reason, soil emissions calculated with this methodology cannot be compared with the above model approaches, which yields total N_2O emissions.

Emission abatement

Emissions from energy, industry, agriculture, waste and land-use sources are also expected to vary in future years, as a result of climate policy. This is described using abatement coefficients, the values of which depend on the scenario assumptions and the stringency of climate policy described in the climate policy component. In scenarios with climate change or sustainability as the key feature in the storyline, abatement is more important than in business-as-usual scenarios. Abatement factors are used for CH_4 emissions from fossil fuel production and transport, N_2O emissions from transport, CH_4 emissions from enteric fermentation and animal waste, and N_2O emissions from animal waste according to the IPCC method. These abatement files are calculated in the IMAGE climate policy sub-model FAIR (Component Climate policy) by comparing the costs of non-CO_2 abatement in agriculture and other mitigation options.

Category: ComponentDescription

Emissions/Policy issues

< Emissions

Parts of Emissions

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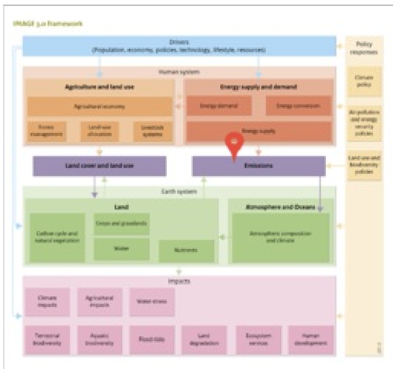

Projects/Applications

Roads from Rio+20 (2012) project

Key publications

Braspenning Radu et al., submitted
Van Vuuren et al., 2006
Van Vuuren et al., 2011b

References

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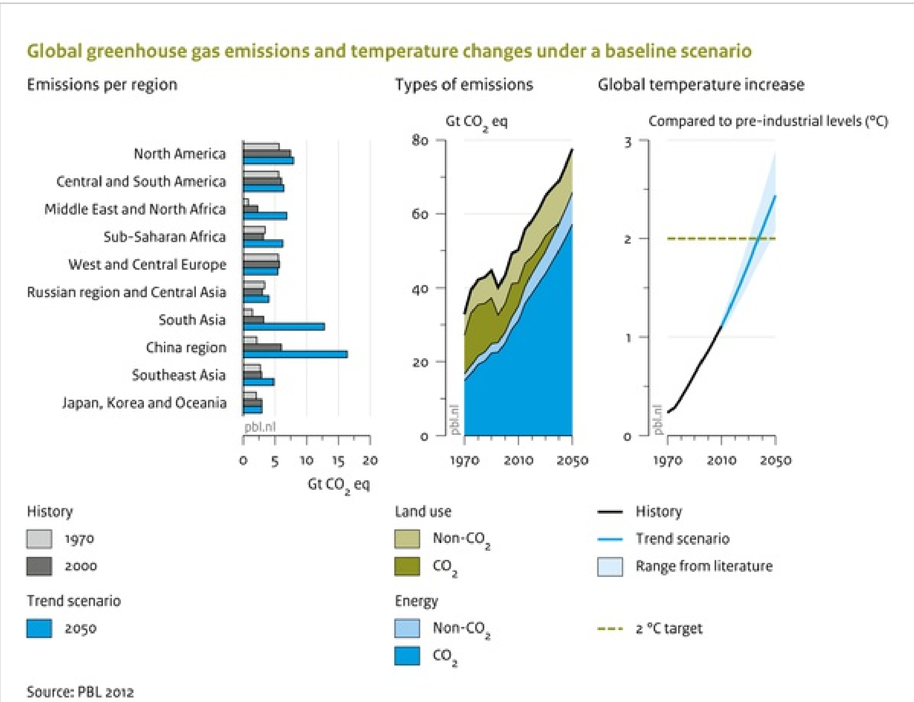
Baseline developments

In a baseline scenario, most greenhouse gas emissions tend to increase, driven by an increase in underlying activity levels (This is shown in the figure below for a baseline scenario for the Rio+20 study (PBL, 2012). For air pollutants, the pattern also depends strongly on the assumptions on air pollution control. In most baseline scenarios, air pollutant emissions tend to decrease, or at least stabilise, in the coming decades as a result of more stringent environmental standards in high and middle income countries.



Future greenhouse gas emissions are mostly driven by an increase in energy use, while the relative contribution of land-use related emissions is projected to decrease.

Policy interventions

Policy scenarios present several ways to influence emission of air pollutants (Braspenning Radu et al., in preparation):

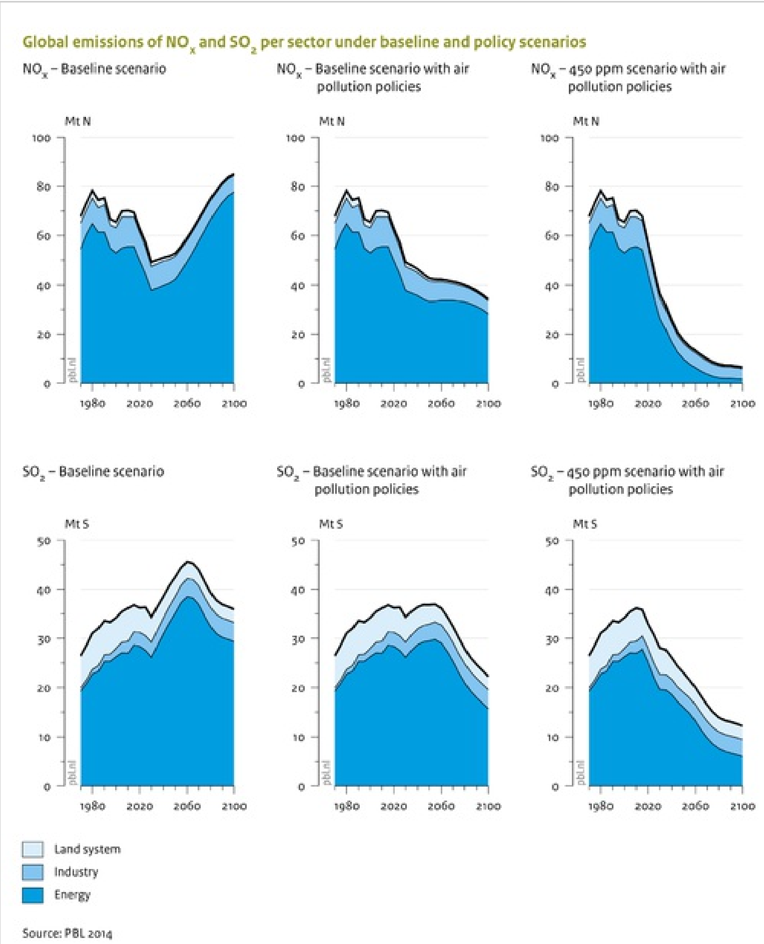
- Introduction of climate policy, which leads to systemic changes in the energy system (less combustion) and thus, indirectly to reduced emissions of air pollutants (Van Vuuren et al., 2006).
- Policy interventions can be mimicked by introducing an alternative formulation of emission factors to the standard formulations (EKC, CLE). For instance, emission factors can be used to deliberately include

maximum feasible reduction measures.

- Policies may influence emission levels for several sources, for instance, by reducing consumption of meat products. By improving the efficiency of fertiliser use, emissions of N_2O, NO and NH_3 can be decreased (Van Vuuren et al., 2011b). By increasing the amount of feed crops in the cattle rations, CH_4 emissions can be reduced. Production of crop types has a significant influence on emission levels of N_2O, NO_x and NH_3 from spreading manure and fertilisers.
- Assumptions related to soil and nutrient management. The major factors are fertiliser type and mode of manure and fertiliser application. Some fertilisers cause higher emissions of N_2O and NH_3 than others. Incorporating manure into soil lowers emissions compared to broadcasting.

The impacts of more ambitious control policies (CLE versus EKC) on SO_2 and NO_x, emissions, and the influence of climate policy are presented in the figure below. Where climate policy is particularly effective in reducing SO_2 emissions, air pollution control policies are effective in reducing NO_x emissions.

See also the Policy interventions Table below.



Climate policy has important co-benefits for air pollution.

Effects of policy interventions on this component

Policy intervention	Description	Effect
Apply emission and energy intensity standards	Apply emission intensity standards for e.g. cars (gCO2/km), power plants (gCO2/kWh) or appliances (kWh/hour).	
Capacity targets	It is possible to prescribe the shares of renewables, CCS technology, nuclear power and other forms of generation capacity. This measure influences the amount of capacity installed of the technology chosen.	
Carbon tax	A tax on carbon leads to higher prices for carbon intensive fuels (such as fossil fuels), making low-carbon alternatives more attractive.	
Change market shares of fuel types	Exogenously set the market shares of certain fuel types. This can be done for specific analyses or scenarios to explore the broader implications of increasing the use of, for instance, biofuels, electricity or hydrogen and reflects the impact of fuel targets. (Reference: Van Ruijven et al., 2007)	
Change the use of electricity and hydrogen	It is possible to promote the use of electricity and hydrogen at the end-use level.	
Excluding certain	Certain energy technology options can be excluded in the model	

Policy intervention	Description	Effect
technologies	for environmental, societal, and/or security reasons. (Reference: Kruyt et al., 2009)	
Implementation of biofuel targets	Policies to enhance the use of biofuels, especially in the transport sector. In the Agricultural economy component only 'first generation' crops are taken into account. The policy is implemented as a budget-neutral policy from government perspective, e.g. a subsidy is implemented to achieve a certain share of biofuels in fuel production and an end-user tax is applied to counterfinance the implemented subsidy. (Reference: Banse et al., 2008)	
Implementation of sustainability criteria in bio-energy production	Sustainability criteria that could become binding for dedicated bio-energy production, such as the restrictive use of water-scarce or degraded areas.	
Improving energy efficiency	Exogenously set improvement in efficiency. Such improvements can be introduced for the submodels that focus on particular technologies, for example, in transport, heavy industry and households submodels.	
REDD policies	The objective of REDD policies it to reduce land-use related emissions by protecting existing forests in the world; The implementation of REDD includes also costs of policies. (Reference: Overmars et al., 2012)	Less emissions due to deforestation and land-use change

Parts of Emissions

Category: ComponentPolicyIssue

Emissions/Data uncertainties limitations

< Emissions

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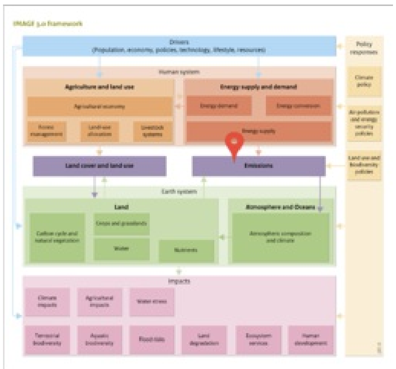

Projects/Applications

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Key publications

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- Van Vuuren et al., 2011b

References

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Data, uncertainties and limitations

Data

Global emission data are provided in a range of inventories. The EDGAR database (JRC/PBL, 2012) was preferred for IMAGE because of its high level of detail and the similar sectoral and regional definitions. Alternative inventories include the database underlying the RAINS/GAINS system, the RETRO database and the RCP database (Lamarque et al., 2010). An overview of available inventories by Granier (2011) has shown large differences between the databases for carbon monoxide, nitrogen oxides, sulphur dioxide and black carbon on global and regional scales. Most emission factors for land-use emissions are based on IPCC methodologies and parameters (IPCC, 2006)

Uncertainties

EDGAR data on activities and emission factors need to be aggregated in order to be used in IMAGE. In this process, decisions need to be made (e.g., on the use of weighted averages and representative sectors), which lead to additional uncertainties. In general terms there are three levels of uncertainty. For energy and industry, emission factors for CO_2 are less uncertain than those for non-CO_2 emissions. In turn, the uncertainty in emission factors for land use and natural sources is larger than for energy and industry sources because of the extreme variability of the factors controlling processes in space and time.

Future emissions and their uncertainty depend on the activity levels determined by other IMAGE components, and on the emission factors. Estimations of future emission factors in the energy and industry systems, described above, rely on historical observations and learning curves. However, future legislation and effective implementation may influence these factors more, and more abruptly. Emission factors for land-use activities may change in the future, also in the absence of climate policy, but are assumed to be constant because of lack of data. As the future development of emission factors is per definition uncertain, the influence is explored by changing the emission factors for different storyline-based scenarios.

Limitations

IMAGE covers almost all emission sources and gases within a consistent framework, based on a few international data sets and authoritative sources. However, some specific emissions are only included as a group, without the underlying production processes. Even more importantly, IMAGE does not include emissions from peat and peat fires, although they constitute an important source of air pollutants and CO_2 emissions (IPCC, 2007a).

Category: ComponentDataUncertaintyAndLimitations

Emissions/References

< Emissions

Key publications

Braspenning Radu et al., submitted
O. Braspenning Radu, M. van den Berg, Z. Klimont, S. Deetman, G. Janssens-Maenhout, M. Muntean, F. Dentener, D.P. van Vuuren (). Exploring synergies between climate and air quality policies using long-term global and regional emission scenarios. Submitted, available on request.

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Carbon capture and storage

For carbon capture and storage (CCS), three different steps are identified in the TIMER model:

- CO_2 capture and compression;
- CO_2 transport;
- CO_2 storage.

Carbon capture is assumed possible for power generation, half of the industrial sector and hydrogen production. In these sectors CCS technologies are defined that compete over market shares with conventional technologies (without CCS). The CCS technologies involve higher costs and a slightly lower conversion efficiency, and are therefore not chosen under default conditions. However, according to model calculations, the costs of these CCS technologies would increase far less compared to conventional technologies if a carbon price would be introduced. Carbon capture is assumed at a maximum of 95%, the remaining 5% is still influenced by the carbon price. The actual market shares of conventional and CCS-based technologies are determined for each market, using multinomial logit equations. The costs of carbon capture are based on Hendriks et al. (Hendriks et al., 2002; Hendriks et al., 2004a; Hendriks et al., 2004b).

The use of CCS increases power generation costs by about 40% to 50%, for natural-gas-fired and coal-fired power plants. Expressed in terms of costs per unit of CO_2, this is roughly equivalent to between USD_{2005} 35 and 45/t CO_2. Similar cost levels are assumed for industrial sources. CO_2 transport costs were estimated for each region and storage category, based on the distance between the main CO_2 sources (industrial centres) and storage sites (Hendriks et al., 2002a). The estimated transport costs vary from USD_{2005} 1 to 30/t CO_2 – the majority being below USD_{2005} 10/t CO_2.

Finally, for each region, the potential for storage categories has been estimated, including:

- empty onshore oil or gas fields;
- operational onshore oil or gas fields;
- empty offshore oil or gas fields;
- operational offshore oil or gas fields;
- enhanced coal-based methane recovery;
- aquifers.

For each category, storage costs were determined, with values typically of USD_{2005} 5 to 10/t CO_2 (Hendriks et al., 2004b).

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Related IMAGE components

- Energy conversion

References

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Category: AdditionalInfo

Energy supply and demand/Technical learning

< Energy supply and demand

An important aspect of TIMER is the endogenous formulation of technology development, on the basis of learning by doing, which is considered to be a meaningful representation of technology change in global energy models (Azar and Dowlatabadi, 1999; Grubler et al., 1999; Wene, 2000). The general formulation of 'learning by doing' in a model context is that a cost measure Y tends to decline as a power function of an accumulated learning measure:

$Y = C * Q^{-\rho}$

where:

- Y is cost measure;
- Q the cumulative capacity or output;
- ρ is the learning rate;
- C is a constant.

Often ρ is expressed by the progress ratio P, which indicates how fast the costs metric, Y, decreases with the doubling of Q ($P=2^{-\rho}$). Progress ratios reported in empirical studies are mostly between 0.65 and 0.95, with a median value of 0.82 (Argotte and Epple, 1990).

In TIMER, learning by doing influences the capital output ratio of coal, oil and gas production, the investment cost of renewable and nuclear energy, the cost of hydrogen technologies, and the rate at which the energy conservation cost curves decline. The actual values used depend on the technologies and the scenario setting. The progress ratio for solar/wind and bioenergy has been set at a lower level than for fossil-based technologies, based on their early stage of development and observed historical trends (Wene, 2000).

There is evidence that, in the early stages of development, P is higher than for technologies in use over a long period of time. For instance, values for solar energy have typically been below 0.8, and for fossil-fuel production around 0.9 to 0.95.

For technologies in early stages of development, other factors may also contribute to technology progress, such as relatively high investment in research and development (Wene, 2000). In TIMER, the existence of a single global learning curve is postulated. Regions are then assumed to pool knowledge and 'learn' together or, depending on the scenario assumptions, are partly excluded from this pool. In the last case, only the smaller cumulated production in the region would drive the learning process and costs would decline at a slower rate.

This page is referred by Energy supply and demand; Energy conversion/Description; Energy supply/Description

Related IMAGE components

- Energy supply
- Energy conversion
- Energy supply and demand

References

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Grid and infrastructure

IIn the IMAGE model, grid and infrastructure are not systematically dealt with. Still, the influence of both factors on transitions – and in particular on the rate of transition – plays a role in the model. There are several places where grid and infrastructure are implicitly or explicitly dealt with.

- Access to electricity is described in the residential model. The model looks at access partly as a function of income and associated investments (Van Ruijven et al., 2012). The access to electricity influences the fuel choice in the residential sector.
- In the power sector, investments into grids are described and added to the costs of electricity. Moreover, in the potential for solar and wind power and related costs, the distance between potential supply and load centres is accounted for (Hoogwijk, 2004).
- In the sub-model on hydrogen power, the large-scale availability of hydrogen as an energy carrier is restricted to the presence of infrastructure. Therefore, originally, only small-scale hydrogen options were available. Only when the volume would reach a certain minimum level, large-scale availability is assumed (hydrogen transport via pipelines), resulting in much lower hydrogen production costs – also in combination with Carbon capture and storage.
- For CCS, a regional estimate was made of the distance between the most important storage sites and the produced CO_2 levels. Therefore, a region- and storage-specific cost factor is added to the on-site storage costs.
- Finally, infrastructure plays a key role in the potential rate of transition. For instance, in transport, electric vehicles could only be introduced at a rate that is consistent with the expansion of corresponding infrastructure to provide power. In the model, this is only implicitly described by adding an additional delay factor on top of the delay that is explicitly taken into account by the lifetime of the technology itself (in this example the electric vehicle). The additional delay factor simply consists of a smoothing function, affecting the portfolio of investments. For the same reason, this smoothing of change in investments is also used elsewhere in the model.

This page is referred by Energy demand/Description; Energy conversion/Description

Related IMAGE components

- Energy demand
- Energy conversion

References

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