To pdf - IMAGE

From IAMC-Documentation

Reference card - IMAGE

About

The reference card is a clearly defined description of model features. The numerous options have been organized into a limited amount of default and model specific (non default) options. In addition some features are described by a short clarifying text.

Legend:

☐ not implemented
☑ **implemented**
☑ **implemented (not default option)**

Name and version IMAGE framework 3.0

Institution and users Utrecht University (UU), Netherlands, http://www.uu.nl.
PBL Netherlands Environmental Assessment Agency (PBL), Netherlands, http://www.pbl.nl.

Documentation IMAGE documentation consists of a referencecard and detailed model documentation

Model scope and methods

Model documentation: Model scope and methods - IMAGE

Objective IMAGE is an ecological-environmental model framework that simulates the environmental consequences of human activities worldwide. The objective of the IMAGE model is to explore the long- term dynamics and impacts of global changes that result. More specifically, the model aims

1. to analyse interactions between human development and the natural environment to gain better insight into the processes of global environmental change;
2. to identify response strategies to global environmental change based on assessment of options and
3. to indicate key inter-linkages and associated levels of uncertainty in processes of global environmental change.

Concept The IMAGE framework can best be described as a geographically explicit assessment, integrated assessment simulation model, focusing a detailed representation of relevant processes with respect to human use of energy, land and water in relation to relevant environmental processes.

Solution method Recursive dynamic solution method

Anticipation Simulation modelling framework, without foresight. However, a simplified version of the energy/climate part of the model (called FAIR) can be run prior to running the framework to obtain data for climate policy simulations.

Temporal dimension Base year:1970, time steps:1-5 year time step, horizon: 2100

Spatial dimension Number of regions:26

1. Canada
2. USA
3. Mexico
4. Rest of Central America
5. Brazil
6. Rest of South America
7. Northern Africa
8. Western Africa
9. Eastern Africa
10. South Africa
11. Western Europe
12. Central Europe
13. Turkey
14. Ukraine +
15. Asian-Stan
16. Russia +
17. Middle East
18. India +
19. Korea
20. China +
21. Southeastern Asia
22. Indonesia +
23. Japan
24. Oceania
25. Rest of South Asia
26. Rest of Southern Africa

Policy implementation Key areas where policy responses can be introduced in the model are:

- Climate policy
- Energy policies (air pollution, access and energy security)
- Land use policies (food)
- Specific policies to project biodiversity
- Measures to reduce the imbalance of the nitrogen cycle

Socio economic drivers

Model documentation: Socio-economic drivers - IMAGE

Exogenous drivers

☑ **Exogenous GDP**
☐ Total Factor Productivity
☐ Labour Productivity
☐ Capital Technical progress
☐ Energy Technical progress
☐ Materials Technical progress
☑ **GDP per capita**

Endogenous drivers

☑ **Energy demand**
☑ **Renewable price**
☑ **Fossil fuel prices**
☑ **Carbon prices**
☑ **Technology progress**
☑ **Energy intensity**
☑ **Preferences**
☑ **Learning by doing**
☑ **Agricultural demand**
☑ **Population**
☑ **Value added**

Development

☑ **GDP per capita**
☑ **Income distribution in a region**
☑ **Urbanisation rate**
☐ Education level
☐ Labour participation rate

Note: GDP per capita and income distrubition are exogenous

Macro economy

Model documentation: Macro-economy - IMAGE

Economic sectors

☐ Agriculture
☐ Industry
☐ Energy
☐ Transport
☐ Services

Note: No explicit economy representation in monetary units. Explicit economy representation in terms of energy is modelled (for the agriculture, industry, energy, transport and built environment sectors)

Cost measures

☐ GDP loss
☐ Welfare loss
☐ Consumption loss
☑ **Area under MAC**
☑ **Energy system costs**

Trade

☑ **Coal**
☑ **Oil**
☑ **Gas**
☑ **Uranium**
☐ Electricity
☑ **Bioenergy crops**
☑ **Food crops**
☐ Capital
☑ **Emissions permits**
☑ **Non-energy goods**
☑ **Bioenergy products**
☑ **Livestock products**

Energy

Model documentation: Energy - IMAGE

Behaviour In the energy model, substitution among technologies is described in the model using the multinomial logit formulation. The multinomial logit model implies that the market share of a certain technology or fuel type depends on costs relative to competing technologies. The option with the lowest costs gets the largest market share, but in most cases not the full market. We interpret the latter as a representation of heterogeneity in the form of specific market niches for every technology or fuel.

Resource use

☑ **Coal**
☑ **Oil**
☑ **Gas**
☑ **Uranium**
☑ **Biomass**

Note: Distinction between traditional and modern biomass

Electricity technologies

☑ **Coal**
☑ **Gas**
☑ **Oil**
☑ **Nuclear**
☑ **Biomass**
☑ **Wind**
☑ **Solar PV**
☑ **CCS**
☑ **CSP**

Note: wind: offshore;
coal: conventional, IGCC, IGCC + CCS, IGCC + CHP, IGCC + CHP + CCS;
oil: conventional, OGCC, OGCC + CCS, OGCC + CHP, OGCC + CHP + CCS);
natural gas: conventional, CC, CC + CCS, CC + CHP, CC + CHP + CCS;
biomass: conventional, CC, CC + CCS, CC + CHP, CC + CHP + CCS

Conversion technologies	☑ **CHP** ☐ Heat pumps ☑ **Hydrogen**	☐ Fuel to gas ☐ Fuel to liquid
Grid and infrastructure	☑ **Electricity** ☐ Gas ☐ Heat	☐ CO2 ☑ **H2**
Energy technology substitution	☑ **Discrete technology choices** ☑ **Expansion and decline**	**constraints** ☑ **System integration constraints**
Energy service sectors	☑ **Transportation** ☑ **Industry**	☑ **Residential and commercial**

Land-use

Model documentation: Land-use - IMAGE; Non-climate sustainability dimension - IMAGE

Land-use	☑ **Forest** ☑ **Cropland** ☑ **Grassland**	☑ **Abandoned land** ☑ **Protected land**

Other resources

Model documentation: Non-climate sustainability dimension - IMAGE

Other resources	☑ **Water** ☑ **Metals**	☐ Cement

Emissions and climate

Model documentation: Emissions - IMAGE; Climate - IMAGE

Green house gasses	☑ **CO2** ☑ **CH4** ☑ **N2O**	☑ **HFCs** ☑ **CFCs** ☑ **SF6**
Pollutants	☑ **NOx** ☑ **SOx** ☑ **BC** ☑ **OC**	☑ **Ozone** ☑ **VOC** ☑ **NH3** ☑ **CO**
Climate indicators	☑ **CO2e concentration (ppm)** ☐ Climate damages $ or equivalent	☑ **Radiative Forcing (W/m^{2})** ☑ **Temperature change (°C)**

Model Documentation - IMAGE

Integrated Model to Assess the Global Environment (IMAGE) 3.0 is a comprehensive integrated modelling framework of interacting human and natural systems. The model framework is suited to large scale (mostly global) and long-term (up to the year 2100) assessments of interactions between human development and the natural environment, and integrates a range of sectors, ecosystems and indicators. The impacts of human activities on the natural systems and natural resources are assessed and how such impacts hamper the provision of ecosystem services to sustain human development.

The model identifies socio-economic pathways, and projects the implications for energy, land, water and other natural resources, subject to resource availability and quality. Unintended side effects, such as emissions to air, water and soil, climatic change, and depletion and degradation of remaining stocks (fossil fuels, forests), are calculated and taken into account in future projections.

1) Model scope and methods - IMAGE

The components of the IMAGE framework are presented in Figure 1, which also shows the information flow from the key driving factors to the impact indicators. Future pathways or scenarios depend on the assumed projections of key driving forces. Thus, all results can only be understood and interpreted in the context of the assumed future environment in which they unfold. As a result of the exogenous drivers, IMAGE projects how human activities would develop, in particular in the energy and agricultural systems. Human activities and associated demand for ecosystem services are squared to the Earth system through the *interconnectors* Land Cover and Land Use, and Emissions.

Assumed policy interventions lead to model responses, taking into account all internal interactions and feedback. Impacts in various forms arise either directly from the model, for example the extent of future land-use for agriculture and forestry, or the average global temperature increase up to 2050. Other indicators are generated by activating additional models that use output from the core IMAGE model, together with other assumptions to estimate the effects, for example, biodiversity (GLOBIO) and flood risks. Currently, impacts emerging from additional models do not influence the outcome of the model run directly. The results obtained can reveal unsustainable or otherwise undesirable impacts, and induce exploration of alternative model assumptions to alleviate the problem. As the alternative is implemented in the linked models, synergies and trade-offs against other indicators are revealed.

To apply IMAGE 3.0, all model settings are adjusted so that the model reproduces the state-of-the-world in 2005. The model calculates the state in 2005 over the period starting in 1970, using exogenous data to calibrate internal parameters. From 2005 onwards, a range of model drivers rooted in more generic narratives and scenario drivers must be prepared either by experts or teams at PBL or in partner institutes to provide inputs, such as population and economic projections. These steps are taken in consultation with stakeholders and sponsors of the studies, and with project partners. An IMAGE run produces a long list of outputs representing the results of the various parts of the framework, either as end indicator or as intermediate inputs driving operations further downstream. Together the outputs span the range from drivers to pressures, states and impacts.

The IMAGE 3.0 model has a wide range of outputs, including:

- energy use, conversion and supply;
- agricultural production, land cover and land use;
- nutrient cycles in natural and agricultural systems;
- emissions to air and surface water;
- carbon stocks in biomass pools, soils, atmosphere and oceans;
- atmospheric emissions of greenhouse gases and air pollutants;
- concentration of greenhouse gases in the atmosphere and radiative forcing;
- changes in temperature and precipitation;
- sea level rise;
- water use for irrigation.

These standard outputs are complemented with additional impact models with indicators for biodiversity, human development, water stress, and flood risks.

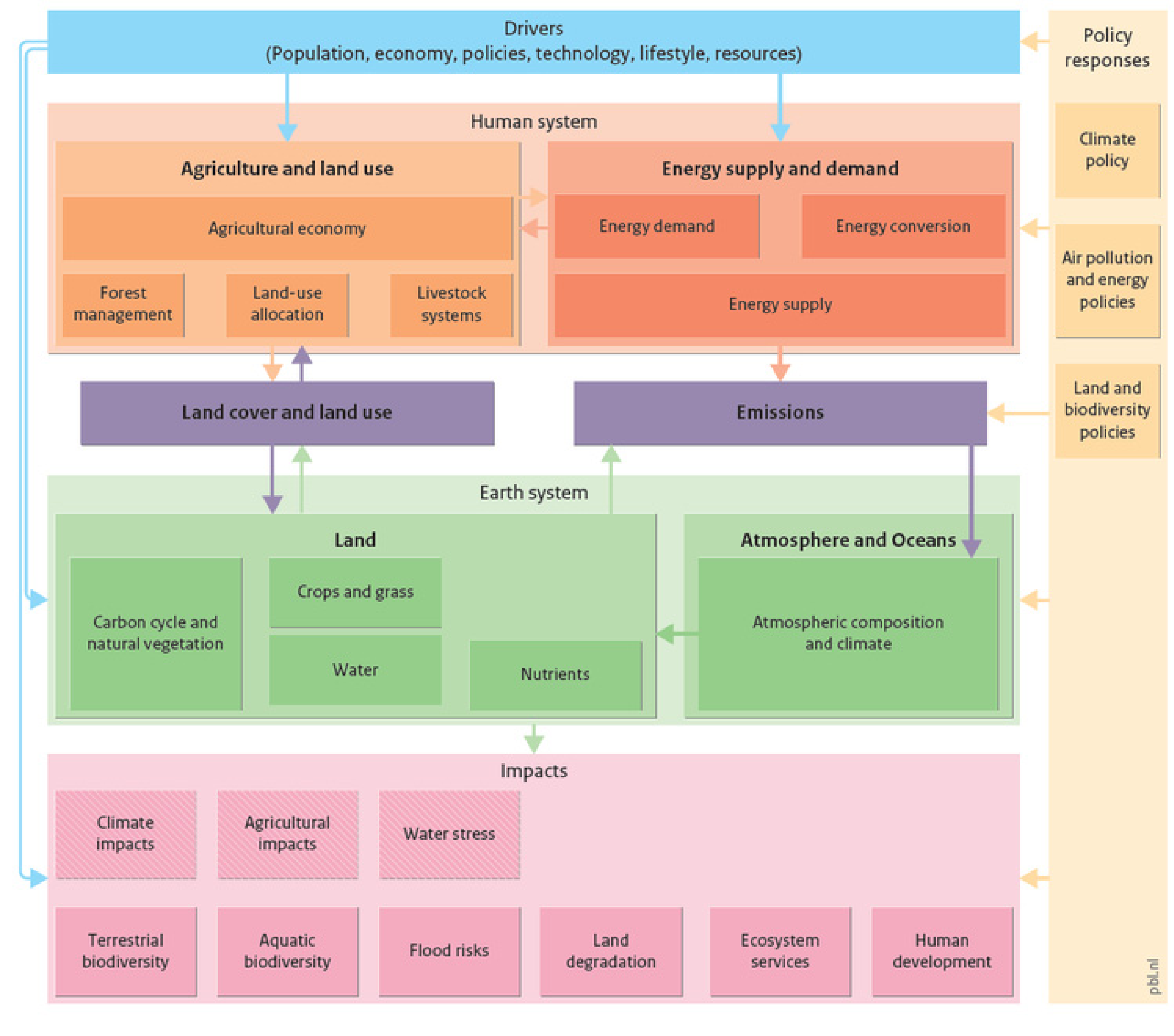

Figure 1: IMAGE 3.0 framework (from IMAGE 3.0 documentation)

1.1) Model concept, solver and details - IMAGE

Objective and scope of IMAGE

IMAGE is a comprehensive integrated modelling framework of interacting human and natural systems. Its design relies on intermediate complexity modelling, balancing level of detail to capture key processes and behaviour, and allowing for multiple runs to explore aspects of sensitivity and uncertainty of the complex, interlinked systems.

The objectives of IMAGE are as follows:

- To analyse large-scale and long-term interactions between human development and the natural environment to gain better insight into the processes of global environmental change;
- To identify response strategies to global environmental change based on assessment of options for mitigation and adaption;
- To indicate key interlinkages and associated levels of uncertainty in processes of global environmental change.

IMAGE is often used to explore two types of issues:

- How the future unfolds if no deliberate, drastic changes in prevailing economic, technology and policy developments are assumed, commonly referred to as baseline, business-as-usual, or no-new-policy assessment;
- How policies and measures prevent unwanted impacts on the global environment and human development.

Features

IMAGE has been designed to be comprehensive in terms of human activities, sectors and environmental impacts, and where and how these are connected through common drivers, mutual impacts, and synergies and trade-offs. IMAGE 3.0 is the latest version of the IMAGE framework models, and has the following features:

- Comprehensive and balanced integration of energy and land systems was a pioneering feature of IMAGE. Recently, other IAMs have been developed in similar directions and comprehensive IAMs are becoming more mainstream.
- Coverage of all emissions by sources/sinks including natural sources/sinks makes IMAGE appropriate to provide input to bio-geochemistry models and complex Earth System Models (ESMs).
- In addition to climate change, which is the primary focus of most IAMs, the IMAGE framework covers a broad range of closely interlinked dimensions. These include water availability and water quality, air quality, terrestrial and aquatic biodiversity, resource depletion, with competing claims on land and many ecosystem services.
- Rather than averages over larger areas, spatial modelling of all terrestrial processes by means of unique and identifiable grid cells captures the influence of local conditions and yields valuable results and insights for impact models.
- IMAGE is based on biophysical/technical processes, capturing the inherent constraints and limits posed by these processes and ensuring that physical relationships are not violated.
- Integrated into the IMAGE framework, [1] (http://www.magicc.org/%7CMAGICC-6) is a simple climate model calibrated to more complex climate models. Using downscaling tools, this model uses the spatial patterns of temperature and precipitation changes, which vary between climate models.
- Detailed descriptions of technical energy systems, and integration of land-use related emissions and carbon sinks enable IMAGE to explore very low greenhouse gas emissions scenarios, contributing to the increasingly explored field of very low climate forcing scenarios.
- The integrated nature of IMAGE enables linkages between climate change, other

environmental concerns and human development issues to be explored, thus contributing to informed discussion on a more sustainable future including trade-offs and synergies between stresses and possible solutions.

IMAGE framework

The IMAGE framework can best be described as an integrated assessment simulation model, that describes the relevant economic and environmental processes with a considerable amount of physical detail. IMAGE has been set-up as an integrated assessment framework in a modular structure, with some components linked directly to the model code of IMAGE, and others connected through soft links (the models run independently with data exchange via data files). This architecture provides more flexibility to develop components separately and to perform sensitivity analyses, recognising that feedback may not always be strong enough to warrant full integration. For example, the various components of the Earth system are fully linked on a daily or annual basis. However, components of the Human system, such as the TIMER energy model and the agro-economic model MAGNET, are linked via a soft link, and can also be run independently.

The IMAGE core model comprises most parts of the Human system and the Earth system, including the energy system, land-use, and the plant growth, carbon and water cycle model LPJmL. The IMAGE framework includes soft-linked models, such as the agro-economic model MAGNET, and PBL policy and impact models, such as FAIR (climate policy), GLOBIO (biodiversity), GLOFRIS (flood risks) and GISMO (human development).

Table 1: IMAGE framework model overview

Computer model	Subject	Developed by
Core computer models		
Fair model	Climate policy and policy response	PBL (http://www.pbl.nl/en)
IMAGE land use model	Land use and global change	PBL (http://www.pbl.nl/en)
LPJmL model	Carbon, vegetation, agriculture and water	PIK (http://www.pik-potsdam.de/)
MAGICC model	Atmospheric composition and climate	MAGICC team (http://wiki.magicc.org/index.php?title=MAGICC_team)
TIMER model	Energy supply and demand	PBL (http://www.pbl.nl/en)
Associated computer models		
CLUMondo model	Land-use allocation	
GISMO model	Impacts on human development	PBL (http://www.pbl.nl/en)
GLOBIO model	Impacts on biodiversity	PBL (http://www.pbl.nl/en)
GLOFRIS model	Flood risk assessment	PBL (http://www.pbl.nl/en), Deltares (http://www.deltares.nl), UU (http://www.uu.nl/EN/Pages/default.aspx), IVM (http://www.ivm.vu.nl)
Related computer models		
GUAM model	Health	PBL (http://www.pbl.nl/en)
Impact model	Agricultural economy	IFPRI (http://www.ifpri.org/)
MAGNET model	Agriculture economy	LEI (http://www.wageningenur.nl/en/Expertise-Services/Research-Institutes/lei.htm)

Computer models are classified in: core, associated and related models.

- Core IMAGE models are used for the integrated assessments projects and developed by the IMAGE team or in close collaboration with partners.
- Associated models use the results of the core models to compute various impacts. These models are developed in consultation with the IMAGE team
- Related models are not part of the IMAGE framework, but may be used in the framework, depending on the type of project. They are not developed by the IMAGE team.

Uncertainty

Systematic uncertainty analyses have been performed on the individual IMAGE models. In addition, IMAGE has been assessed in model comparison projects (e.g., Energy Modelling Forum, AMPERE, LIMITS and AgMIP via MAGNET) [1]. These studies also contribute to understanding key uncertainties, as the experiments in these projects tend to be set up in the form of sensitivity runs, in which comparison with other models provides useful insights. An overview of key uncertainties in the IMAGE framework is presented in the table below.

Table 2: Overview of key uncertainties in IMAGE 3.0

Model component	Uncertainty
Drivers	Overall population size, economic growth
Agricultural systems	Yield improvements, meat consumption, total consumption rates
Energy systems	Preferences, energy policies, technology development, resources
Emissions	Emission factors, in particular those in energy system
Land cover / carbon cycle	Intensification versus expansion, effect of climate change on soil respiration, CO2, fertilization effect
N-cycle	Nutrient use efficiencies
Water cycle	Groundwater use, patterns of climate change
Climate system	Climate sensitivity, patterns of climate change
Biodiversity	Biodiversity effect values, effect of infrastructure and fragmentation

1.3) Temporal dimension - IMAGE

The Human system and the Earth system each run at annual or five-year time steps focusing on long-term trends to capture inertia aspects of global environmental issues. In some IMAGE model components, shorter time steps are also used, for example, in water, crop and vegetation modelling, and in electricity supply. The model is run up to 2050 or 2100 depending on the issues under consideration. For instance, a longer time horizon is often used for climate change studies. IMAGE also runs over the historical period 1971-2005 in order to test model dynamics against key historical trends.

The model does not use foresight. However, a simplified version of the energy/climate part of the model (called FAIR) can be run separately for cost-optimisation over time. The outcomes of this model can be fed back into the framework as whole to determine detailed outcomes for climate policy simulations.

1.4) Spatial dimension - IMAGE

The Human system and the Earth system in IMAGE 3.0 are specified according to their key dynamics. The geographical resolution for socio-economic processes is 26 regions defined based on their relevance for global environmental and/or development issues, and the relatively high degree of coherence within these regions (figure below). In the Earth system, land use and land-use changes are presented on a grid of 5x5 minutes, while the processes for plant growth, carbon and water cycles are modelled on a 30 x 30 minutes (0.5 x 0.5 degree) resolution.

Trade

The following products are traded in the IMAGE framework: energy carriers (fossil fuels, biomass and hydrogen), CO_2 certificates, steel and cement, crops and livestock products (not the livestock itself). The way trade is modeled differs by product. In the energy system, trade is described by assuming that each region imports and exports products to every other region; allocation is done using multinomial logit functions that assign market share on the basis of the costs of the product, the costs of transport and a preference factor. The trade of agricultural products is determined using a computable general equilibrium model (CGE) called MAGNET that is coupled to IMAGE.

Spillovers

Several relationships exists between the IMAGE regions that can result in spillovers. As described in the previous paragraph, the IMAGE regions are coupled via trade. This implies that policies introduced in one region can influence trends in another region. This is the case for energy products, but also for land-use products. While the first can directly influence emissions, the latter can impact land use and therefore indirectly emissions. In the model, policies can also lead to spill-over of technologies on the basis of the learning curves in the model. However, the impact of this is relatively weak in IMAGE.

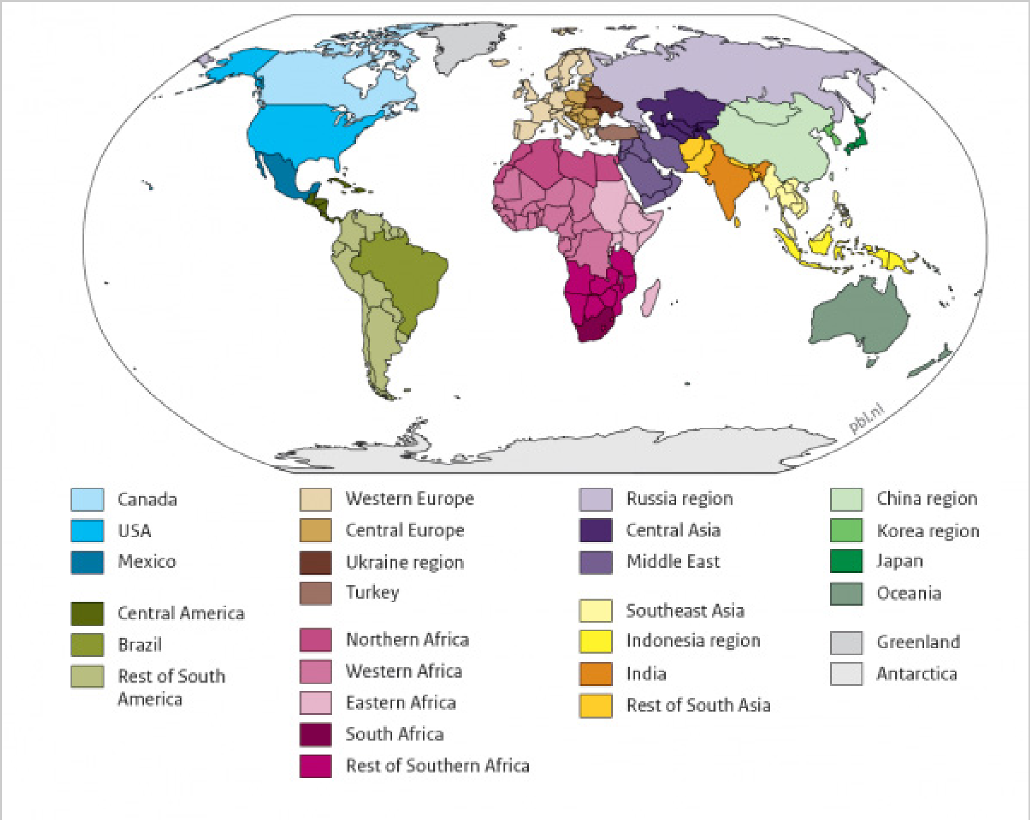

Figure 2: The 26 world regions in IMAGE 3.0 (from IMAGE 3.0 documentation)

1.5) Policy - IMAGE

The IMAGE framework can be used to explore types of policy issues in a variety of areas. These include possible impacts in the absence of new policies or policy responses, and evaluation of possible policy interventions. IMAGE provides an integrated perspective on policy issues by assessing options in various part of the Human and Earth systems and evaluating the impact from several perspectives. The model assesses the following key areas for policy responses:

- Climate policy (global targets, regional efforts, costs and benefits)
- Energy policies (air pollution, energy access, energy security and bioenergy)
- Land and biodiversity policies (food, bioenergy, nature conservation)
- Human development policies (malnutrition, health)
- Measures to reduce the imbalance of nutrient and water cycles.

The first three are discussed below.

Climate policy

A key focus of the IMAGE framework is climate change mitigation strategies. For this purpose, IMAGE is linked to the FAIR model to assess detailed climate policy configurations in support of negotiation processes, and also for inter-temporal optimisation of mitigation strategies. FAIR receives information from various parts of IMAGE, including baseline emissions from energy, industry and land use, the potential for reforestation, and the costs to emission abatement in the energy system. The latter is provided in dynamic marginal abatement cost (MAC) curves, based on the IMAGE energy model, for different regions, gases and sources. Using demand and supply curves, the model determines the carbon price on the international trade market, and the resulting net abatement costs for each region. Long-term reduction strategies can be determined by minimising cumulative discounted mitigation costs. The FAIR results are fed back to the core IMAGE model to calculate impacts on the energy and land-use systems. Together, FAIR and IMAGE can be used to assess the relative importance of mitigation measures and the potential impacts of climate policy, such as avoided damage and co-benefits for air pollution.

Energy policies

The IMAGE framework can be used to assess a wider range of energy policies than climate policy alone, including measures to promote access to modern energy (moving away from fossil fuels and traditional biomass, and providing access to electricity) and to improve energy security. Moreover, it is possible to constrain or even ban the use of specific technologies, such as bioenergy, nuclear power and carbon capture storage. IMAGE analysis incorporates linkages, synergies and trade-offs in global change processes, such as the link between energy use and land use for bioenergy, and the consequences of air pollution for human health.

Land and biodiversity policies

Policies on land use and biodiversity can be introduced in the various IMAGE components. These include changes in the agro-economic model (trade policies, subsidies, taxes, yield improvements, and dietary preferences) and the land-use system (restriction on certain land use types, REDD). As a linked system, IMAGE can assess the system-wide consequences of measures introduced, including trade-offs and feedbacks, such as the consequences of agricultural policies for nutrient cycles, biodiversity and hunger. Key examples are evaluation of dietary changes with respect to biodiversity, land-use and greenhouse gas emissions, and evaluation of more stringent land-use planning and REDD on biodiversity conservation and food security.

2) Socio-economic drivers - IMAGE

To explore future scenarios, exogenous assumptions need to be made for a range of factors that shape the direction and rate of change in key model variables and results. Together with the endogenous functional relationships and model parameters that typify model behaviour, these exogenous assumptions drive the outcome of model calculations. These assumptions are the drivers that determine the model results, subject to the assumed external conditions.

In IMAGE, six groups of assumptions are distinguished that make up the scenario drivers. These six groups are the basis for all scenarios and are embedded in a scenario narrative or storyline. This includes cases where current trends and dynamics are assumed to continue into the future, commonly referred to as reference or *business-as usual* scenarios. But scenario drivers can also be used to describe a set of contrasting futures to explore the relevant range of uncertain yet plausible developments.

As a rule, scenario drivers are not numerical model inputs but, in qualitative or semiquantitative terms, govern a detailed set of exogenous assumptions in terms of model input to the various components of the model framework. Numerical model drivers for a specific scenario are established on the basis of the six generic scenario drivers.

The scenario drivers and underlying narrative, together with the quantitative model drivers, form a scenario that is inextricably linked with the results from an IMAGE scenario run.

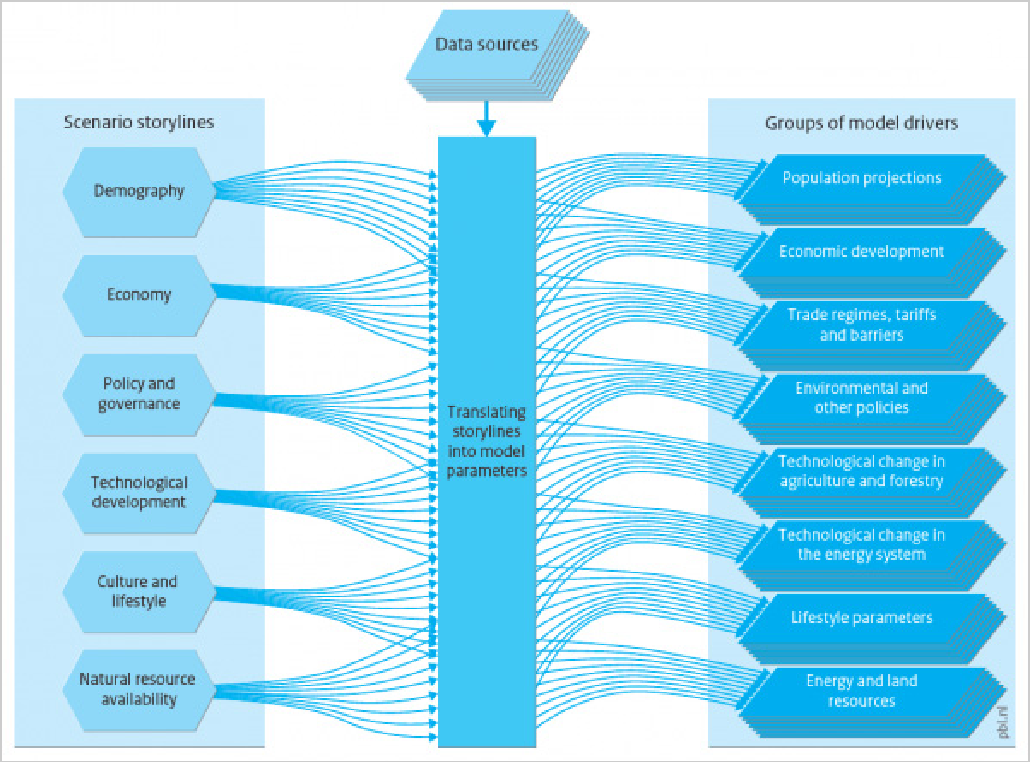

Figure 3: Scenario development and model drivers IMAGE 3.0

2.1) Population - IMAGE

The future state of the world depends on the population because total demand for goods and services equals the number of people times demand per capita.

Most population projections used as input to the IMAGE model have been adopted from published sources, such as data from the United Nations [2] and projections by the International Institute for Applied Systems Analysis (IIASA) [3]. Behind these numerical projections are economic, technical, educational and policy assumptions that determine the estimated future population as the net outcome of fertility and mortality, adjusted for migration flows. This has provided internally consistent, overall population scenarios on the basis of underlying demographic trends.

In addition to total number of people, the population is broken down into gender, income classes, urban and rural, and educational level. These attributes are relevant for issues such as consumption preferences and patterns, and access to goods and services. Using a downscaling procedure [4], national and regional population can be projected at grid level to account for trends in urbanisation and migration within countries and regions.

Population data are used in energy and agricultural economics modelling, and in other IMAGE components, such as water stress, nutrients, flood risks and human health.

2.2) Economic activity - IMAGE

At the most aggregated level, economic activity is described in terms of gross domestic product (GDP) per capita. Models outside the IMAGE 3.0 framework, such as the OECD ENV-Growth model, project long-term GDP growth based on developments in key production factors (e.g., capital, labour, natural resources), and the sector composition of the economy. The various components of GDP on the production side (in particular value added (VA) per sector) and expenditures (in particular private consumption) are estimated with more detailed models that take account of inter-sector linkages, own and cross-price responses, and other factors [5].

In IMAGE 3.0, economic variables are used as model drivers for the energy demand model, and non-agricultural water demand contributing to water stress. To meet the requirements of the household energy demand model, average income is broken down into urban and rural population, and each population into quintiles of income levels. The latter is derived from the assumed uneven income distribution using the GINI factor, a measure of income disparity in a population. The macro indicator GDP per capita is also used directly in IMAGE components, such as human health, flood risk, and nutrients (for calculating urban wastewater). The agriculture model MAGNET is an economy-wide computable general equilibrium (CGE) model that reproduces exogenous GDP growth projections made in less complex economic growth models.

3) Macro-economy - IMAGE

At the most aggregated level, economic activity is described in terms of gross domestic product (GDP) per capita. Models outside the IMAGE 3.0 framework, such as the OECD ENV-Growth model, project long-term GDP growth based on developments in key production factors (e.g., capital, labour, natural resources), and the sector composition of the economy. The various components of GDP on the production side (in particular value added (VA) per sector) and expenditures (in particular private consumption) are estimated with more detailed models that take account of inter-sector linkages, own and cross-price responses, and other factors [5].

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3.1) Production system and representation of economic sectors - IMAGE

For comparable levels of affluence, observed consumption behaviour differs greatly between countries and regions, and to a lesser extent within countries. The modal split for passenger transport by walking, bicycle, car, bus, train, boat and aircraft depends on income, but also on engrained traditions and habits of social groups. Food preferences depend on availability and affordability, and also greatly on cultural factors, such as religion (e.g., no pork for Jewish and Islamic households, and no beef or no meat at all for Hindus), and on tradition, values and health concerns. In addition, behaviour may be influenced by concerns about environmental degradation, animal welfare, inter-regional and inter-generational equity, and other issues according to dominant social norms and values.

Consumer preferences and lifestyles may change over time, as may norms and values. The direction and rates of change can be inferred from the underlying scenario storyline. Policies may be put in place to enable, encourage or even induce change, given sufficient public support.

4) Energy - IMAGE

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 [6][7]. 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.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 macro-economic 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 [8] and GCAM [9].

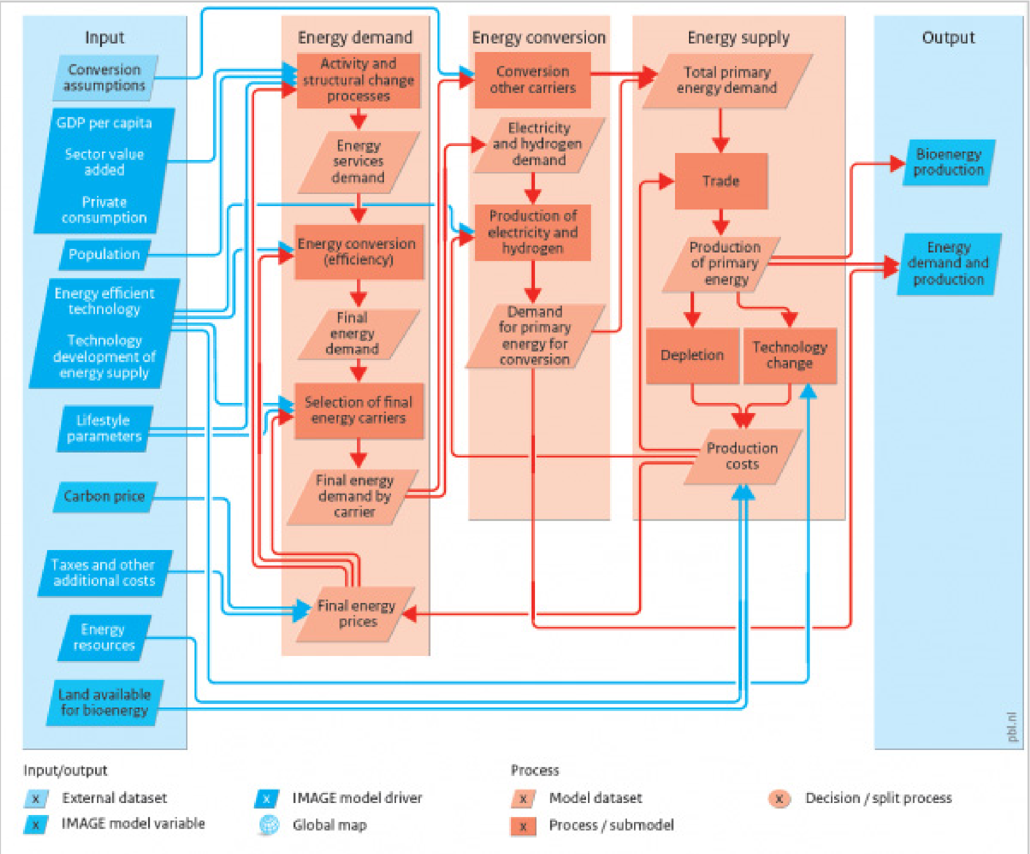


Figure 4: TIMER, the energy demand and supply model in IMAGE 3.0

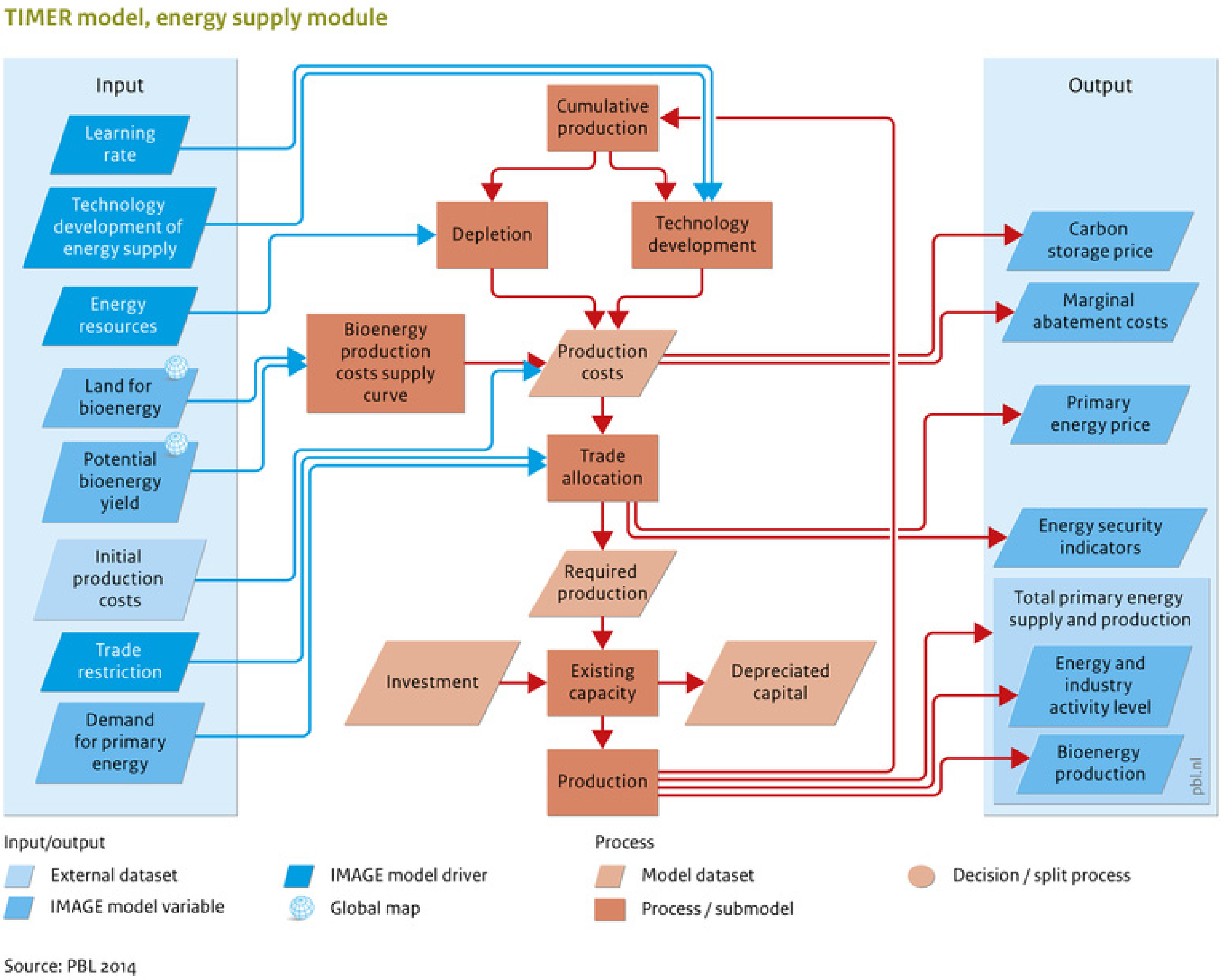
4.1) Energy resource endowments - IMAGE

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. An overview of the general energy supply model structure is provided in Figure 5.


TIMER model, energy supply module

Source: PBL 2014

Figure 5: Flowchart Energy supply.

Fossil fuels, uranium and fissile resources

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 cost levels. The model assumes that the cheapest deposits will be exploited first taking into account trade costs between regions. 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 3: Main assumptions on fossil fuel resources[1][2]

	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)	46.2	498.6	1.3	23.0
Total	65	519.2	168.6	270.0

Fossil fuel resources are aggregated to five resource categories for each fuel (see table above). Each category has typical production costs. The resource estimates for oil and natural gas 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.

Bioenergy

The structure of the biomass submodule is similar to that for fossil fuel supply, but with the following differences [10]:

- 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 km2, which was found to be a reasonable proxy for regional differences in land rent costs. The production functions are calibrated to empirical data [10].
- 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, N2O from fertilisers, energy) are estimated, and are subject to carbon tax, where relevant.

Wind and solar energy

Potential supply of renewable energy (wind, solar and bioenergy) is estimated generically as follows [10][11]:

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 [12].
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.

4.1.1) Fossil energy resources - IMAGE

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 cost 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 4: Main assumptions on fossil fuel resources[1][2]

	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
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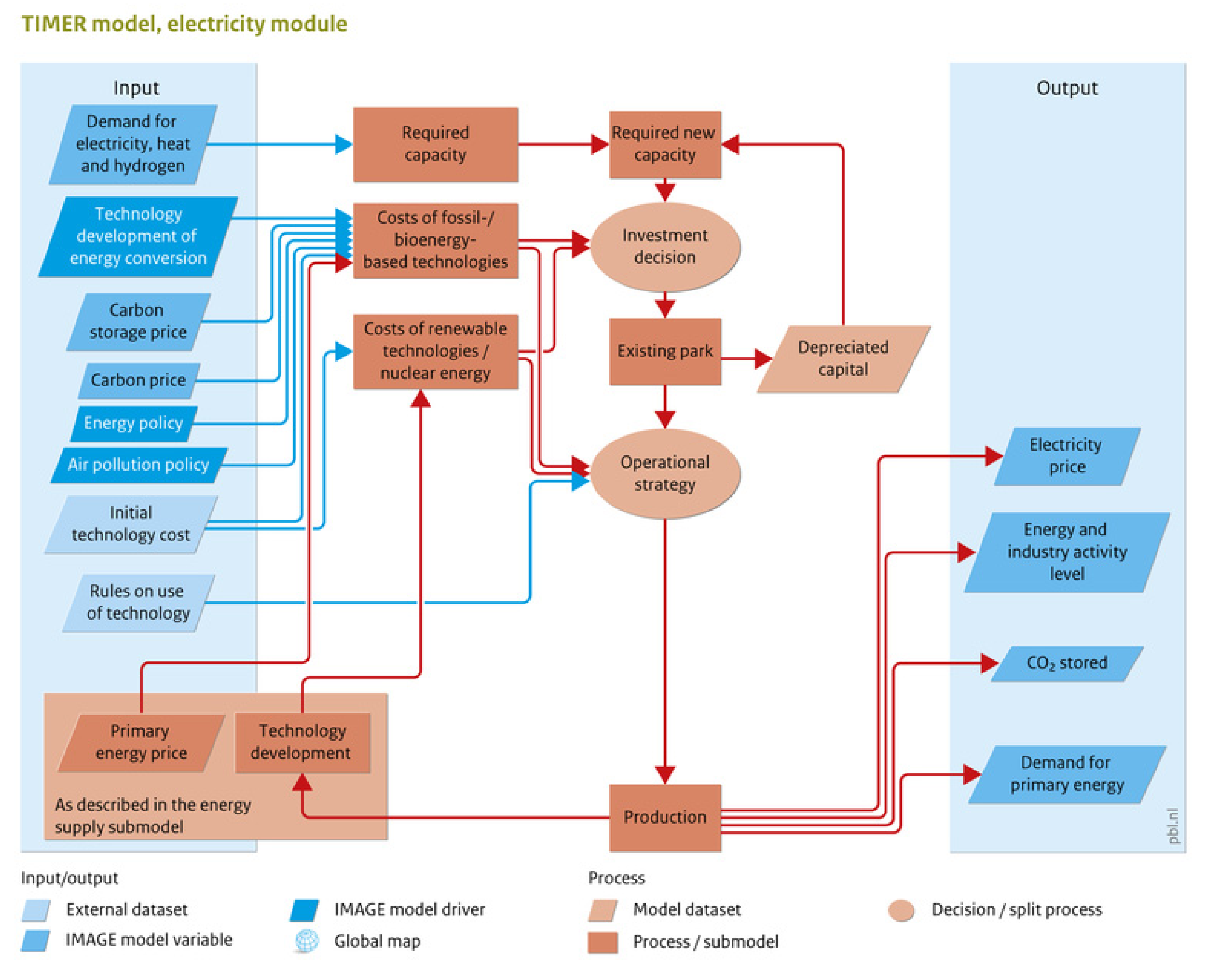
4.2) Energy conversion - IMAGE

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. More details on the energy conversion modelling can be found on the Electricity, Heat and Gaseous fuels pages.

An overview of the energy conversion model structure is provided in Figure 6.

4.2.1) Electricity - IMAGE



Source: PBL 2014

Figure 6: Flowchart Energy conversion.

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 [10][7].

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. 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 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 use

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) [13]. 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 (fueled 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 CO2 storage cost.

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 ; depletion by long-term 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 [10].

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 [10]. 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. A small trade model for these fission fuels is included.

4.2.2) Heat - IMAGE

Central heat demand is satisfied by a price-determined mix of solid, liquid and gaseous fuels. An efficiency factor determines the final supply of primary energy. Heat can be produced by heat production units and combined heat and power units. Heat production units only produce heat. Combined heat and power units produce both heat and electricity, increasing the overall efficiency of the plant. The produced electricity is used to supply demand for electricity. Stocks and lifetimes of heat capacity are explicitly modeled.

4.2.3) Gaseous fuels - IMAGE

The description of fossil fuel production is described under Energy resource endowments. On this page we focus on hydrogen production.

Hydrogen

The structure of the hydrogen generation submodule is similar to that for electric power generation [14] but with following differences:

- There are only eleven supply options for hydrogen production from 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; and small methane reform plants.
- 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.
- Intermittence does not play an important role because hydrogen can be stored to some degree. Thus, there are no equations simulating system integration.
- Hydrogen can be traded. A trade model is added, similar to those for fossil fuels.

4.2.6) Grid, pipelines and other infrastructure - IMAGE

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

- In the residential model, access to electricity is described. The model looks at access partly as a function of income and associated investments. The method has been described by van Ruijven et al. [15] to look into the question whether access goals can be achieved in the next decades. The access to electricity influences the fuel choice in the residential sector.
- In the power sector, investments into grid are described and add to the costs of electricity. Moreover, in the potential of solar and wind and related costs the distance between potential supply and load centers is accounted for [10].
- In the hydrogen submodel, large-scale available of hydrogen as energy carrier is restricted by the presence of infrastructure. Therefore, originally only small-scale hydrogen option are available. Only when the volume gets above a certain minimum level, it is assumed that large-scale options become available (transport of hydrogen via pipes) providing the option of much lower costs hydrogen production also in combination with CCS.

- For CCS, an estimate is made by region of the distance between the most important storage sites and the production of CO2. Therefore, a region-specific and storage-option specific cost factor is added to the on-site storage costs.
- Finally, infrastructure plays in reality a key-role in the potential rate of transition: for instance, in transport electric vehicles can 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.

4.3) Energy end-use - IMAGE

IMAGE contains a detailed description of the energy service consumption in the transport, residential, cement and steel sector. In these sectors the physical activity (e.g passenger km, tonne km, tonne cement, tonne steel and residential floor space) are projected which drive the sectors demand for energy. Modelling energy services gives the opportunity to better assess scenarios of structural change (e.g. in the transport sector modal shift), technology efficiency and saturation effects. More details on the transport, industry and residential modelling can be found on the Transport, Industrial sector and Residential and Commercial sectors pages.

4.3.1) Transport - IMAGE

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. [16]. There are seven passenger transport 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. An overview of the transport passenger model structure is provided in Figure 7.

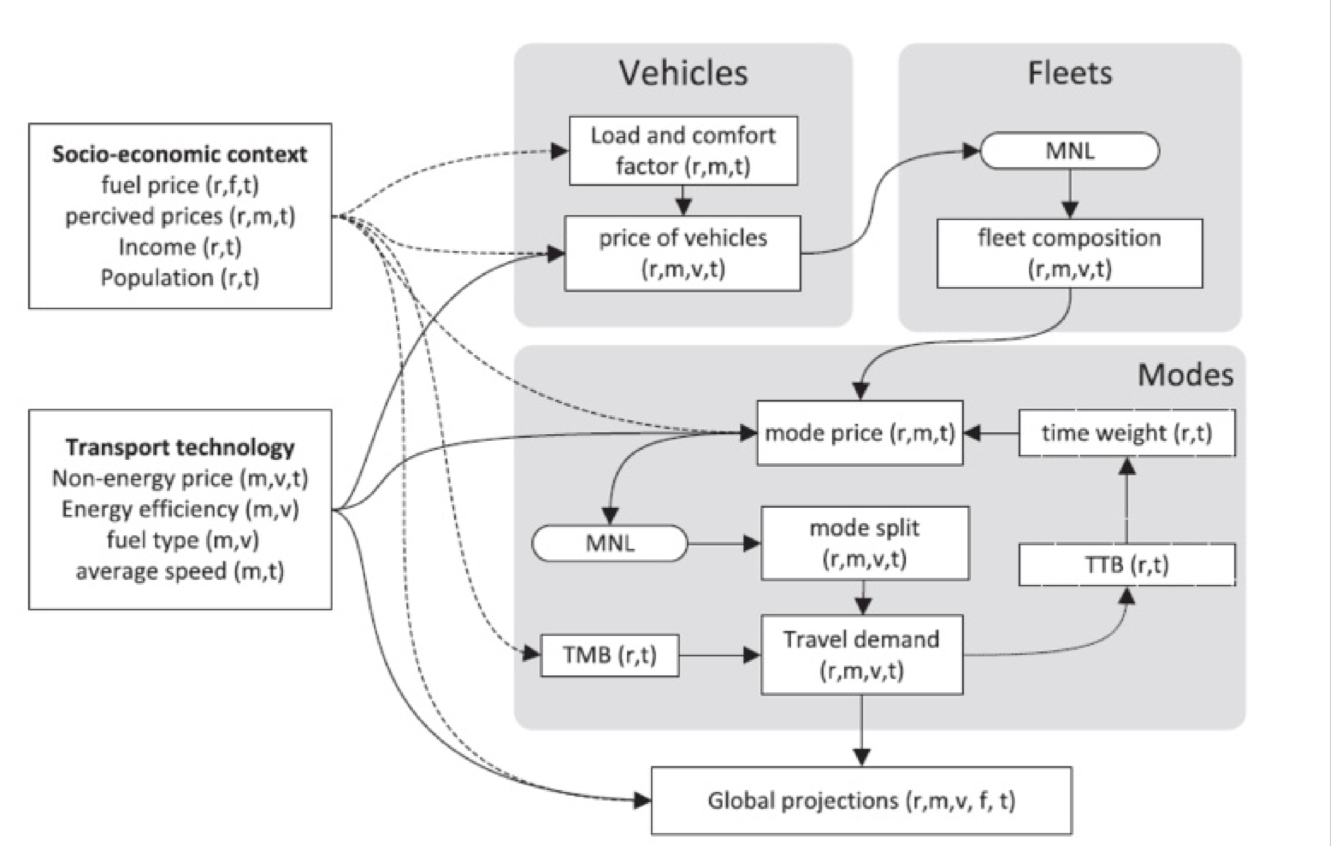


Figure 7: Overview of the TRAVEL model. The indices r, m, v, f, t denote region, travel mode, vehicle type, fuel type and time, respectively.

[16]

The freight transport submodule has a simpler structure. Service demand is projected with constant elasticity of the industry value added for each freight 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. There are six freight transport modes: international shipping, domestic shipping, train, heavy truck, medium truck and aircraft.

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 in both the passenger and freight transport submodules. These substitution processes describe the price induced energy efficiency changes. Over time efficient technologies become more competitive due to exogenous assumed decrease in cost, representing the autonomous induced energy efficiency. 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 (or in case of a hybrid vehicle two) fuel type, this process also describes the fuel selection.

4.3.2) Residential and commercial sectors - IMAGE

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 in [17] and [18].

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 is 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 [17]. 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 [15]. 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 0.5x0.5 degree grid, from which a stylised power grid is derived and analysed to determine investments in low-, medium- and high-voltage lines and transformers.

4.3.3) Industrial sector - IMAGE

The heavy industry submodule was included for the steel and cement sectors[19]. 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 in the demand section. 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).

An overview of the heavy industry model structure is provided in Figure 8, and a more detailed description of the model is given in van Ruijven et al. (2016) [19].

[19]

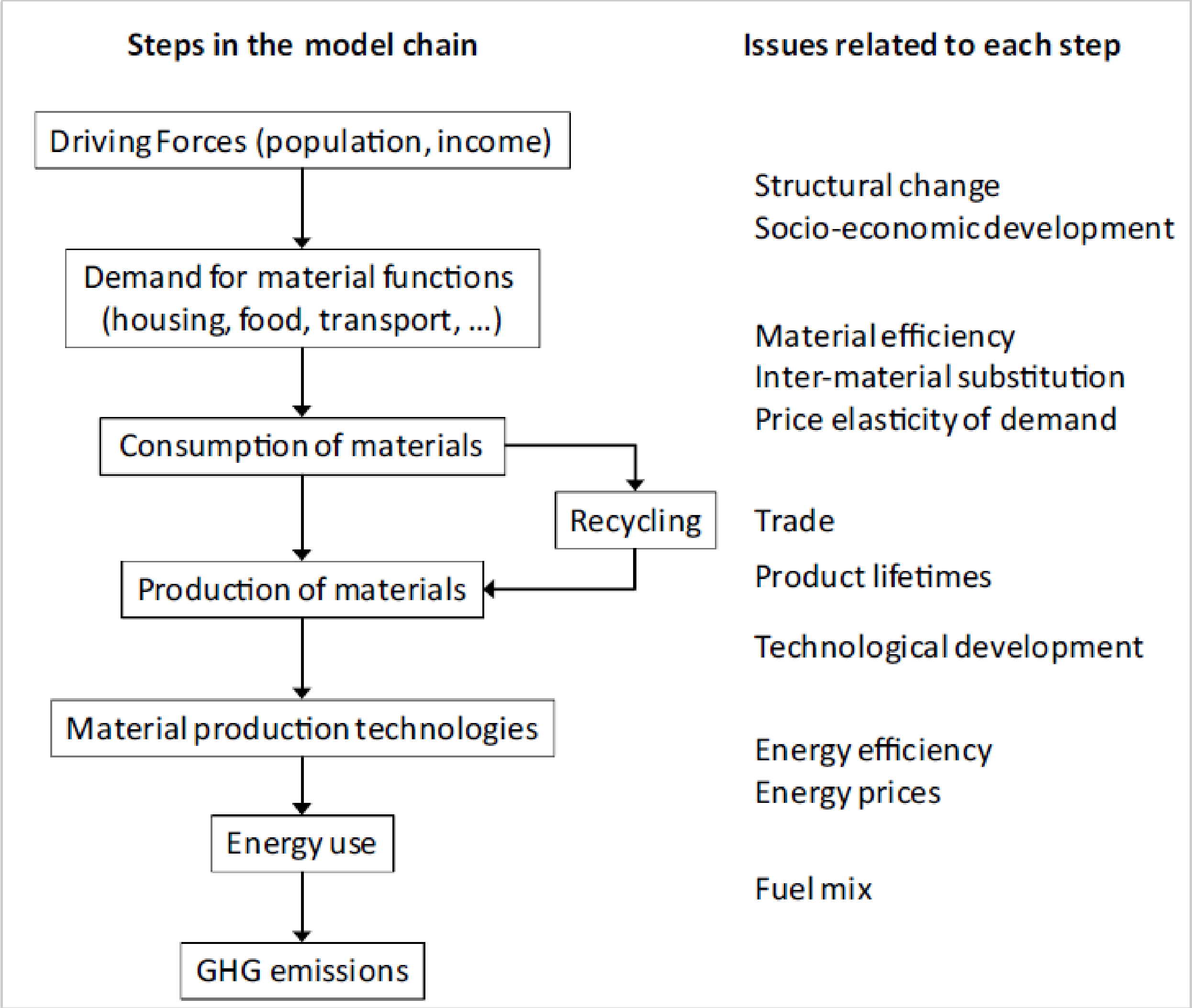


Figure 8: Overview of the heavy industry model.

4.3.4) Other end-use - IMAGE

CCS

For carbon capture and storage, three different steps are identified in the TIMER model: CO_2 capture and compression, CO_2 transport and CO_2 storage. Capture is assumed to be possible in electric power production, half of the industry sector and hydrogen production. Here, alternative technologies are defined that compete for market share with conventional technologies (without CCS). The former have higher costs and slightly lower conversion efficiencies and are therefore not chosen under default conditions; however, these technologies increase much less in price if a carbon price is introduced in the model. Capture is assumed to be at a maximum 95%; the remaining 5% is still influenced by the carbon price. The actual market shares of the conventional and CCS based technologies are determined in each market using multinomial logit equations. The capture costs are based on Hendriks et al. [20][13][21]. In the electric power sector, they increase generation costs by about 40-50% for natural gas and coal-based power plants. Expressed in terms of costs per unit of CO_2, this is equivalent to about

35-45\$/tCO_2. Similar cost levels are assumed for industrial sources. CO_2 transport costs were estimated for each region and storage category on the basis of the distance between the main CO2 sources (industrial centres) and storage sites [21]. The estimated transport costs vary from 1-30 \$/tCO_2 the majority being below 10\$/tCO_2. Finally, for each region the potential for 11 storage categories has been estimated (in empty and still existing oil and gas fields, and on- and offshore thus a total of 8 combinations); enhanced coal-based methane recovery and aquifers (the original aquifer category was divided into two halves to allow more differentiation in costs). For each category, storage costs have been determined with typical values around 5-10\$/tCO_2 [21]. The model uses these categories in the order of their transport and storage costs (the resource with lowest costs first).

4.4) Energy demand - IMAGE

Demand is calculated in terms of physical parameters (EJ, tons of grains etc). The demand types represented include energy, agricultural products, and water. Also for timber there is a relatively simple representation. For residential energy use income and urban/rural distribution are taken into account.

Energy demand

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.

In the TIMER energy demand module, final energy demand is simulated as a function of changes in population, economic activity and energy intensity. 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. The detailed energy end use models are described in the IMAGE energy section. Energy prices link the demand module with other parts of the energy model, as they respond dynamically to changes in demand, supply and conversion.

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:

in which:

represents final energy;
represents population;

the sectoral activity per capita;

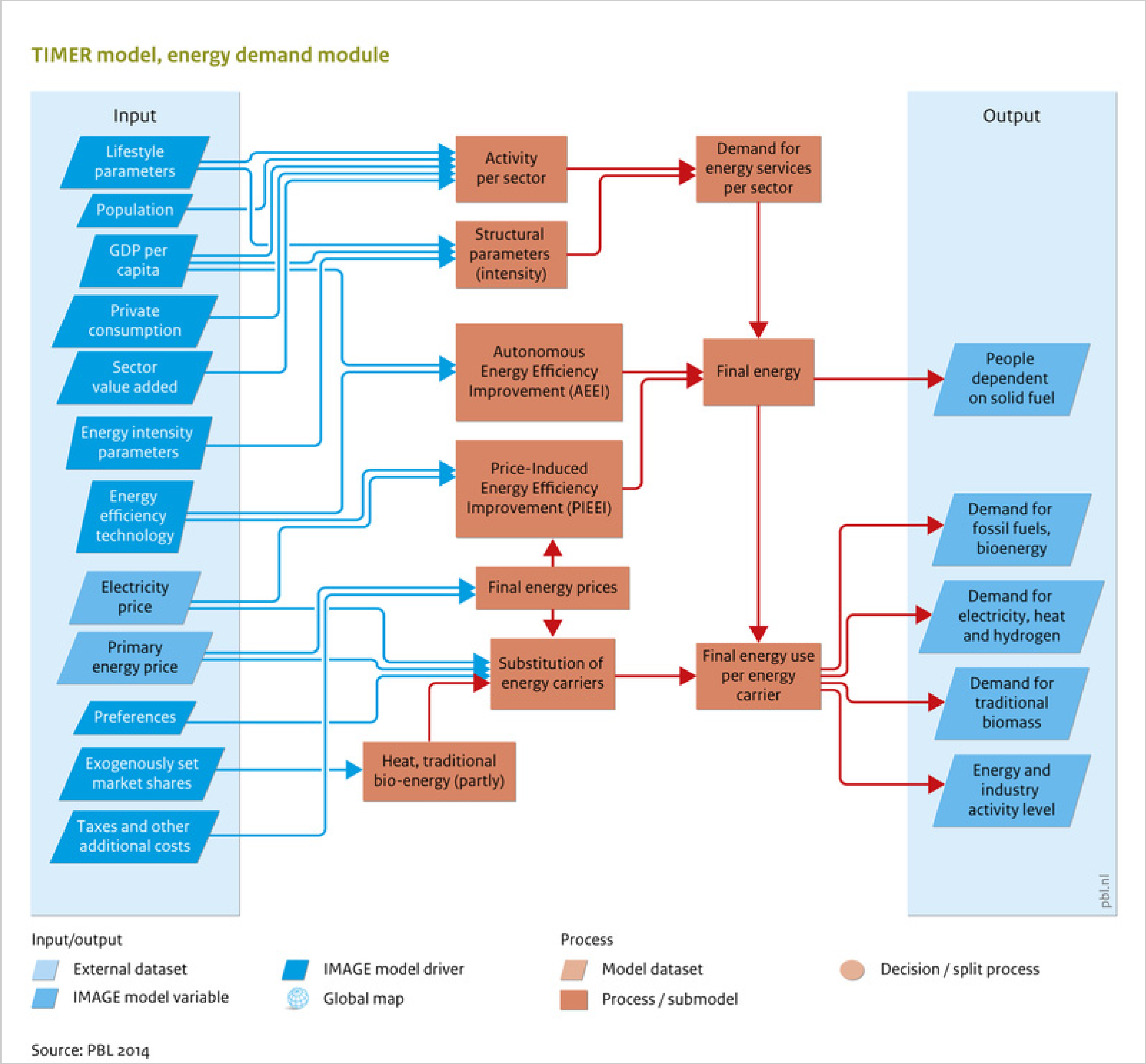
a factor capturing intra-sectoral structural change;
the autonomous energy efficiency improvement;
the price-induced energy efficiency improvement.

In the denominator:

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

Population and economic activity levels are exogenous inputs into the module.

An overview of the energy demand model structure is provided in Figure 9.


TIMER model, energy demand module

Source: PBL 2014

Figure 9: Flowchart Energy demand.

4.5) Technological change in energy - IMAGE

Technological change in the energy model TIMER

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 [22][23][24]. 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, where n is the learning rate, Q the cumulative capacity or output, and C is a constant:

Failed to parse (syntax error): {\displaystyle \[Y = C * Q^{-n}\]}

Often n is expressed by the progress ratio p, which indicates how fast the costs metric Y decreases with doubling of Q (p=2-n). Progress ratios reported in empirical studies are mostly between 0.65 and 0.95, with a median value of 0.82 [25].

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 [24].

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 [24]. 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.

Technology substitution in the energy model TIMER

The indicated market share (IMS) of a technology is determined using a multinomial logit model that assigns market shares to the different technologies (i) on the basis of their relative prices in a set of competing technologies (j).

Failed to parse (syntax error): {\displaystyle \[MS_{i}=\frac{e^{\lambda x_{i}}}{\sum_je^{\lambda c_{j}}}\]}

MS is the market share of different technologies and c is their costs. In this equation, is the so-called logit parameter, determining the sensitivity of markets to price differences.

The equation takes account of direct 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.

5) Land-use - IMAGE

Land cover and use are changed by humans for a variety of purposes, such as to produce food, fibres, timber and energy, to raise animals, for shelter and housing, transport infrastructure, tourism, and recreation. These human activities have affected most areas in the world, transforming natural areas to human-dominated landscapes, changing ecosystem structure and species distribution, and water, nutrient and carbon cycles. Natural landscape characteristics and land cover also affect humans, determining suitable areas for settlement and agriculture, and delivering a wide range of ecosystem services. As such, land cover and land use can be understood as the complex description of the state and processes in a land system in a certain location. It results from the interplay of natural and human processes, such as crop cultivation, fertilizer input, livestock density, type of natural vegetation, forest management history, and built-up areas.

In IMAGE, elements of land cover and land use are calculated in several components, namely in land use allocation, forest management, livestock systems, carbon cycle and natural vegetation. The output from these components forms a description of gridded global land cover and land use that is used in these and other components of IMAGE. In addition, this description of gridded land cover and land use per time step can be provided as IMAGE scenario information to partners and other models for their specific assessments.

Model description

Land cover and land use described in an IMAGE scenario is a compilation of output from various IMAGE components. This compilation provides insight into key processes in land-use change described in the model and an overview of all gridded land cover and land use information available in IMAGE. Land cover and land use is also the basis for the land availability assessment, which provides information on regional land supply to the agro-economic model , based on potential crop yields, protected areas, and external datasets such as slope, soil properties, and wetlands.

5.1) Agriculture - IMAGE

Introduction

As a result of the growing world population and higher per capita consumption, production of food, feed, fibres and other products, such as bioenergy and timber, will need to increase rapidly in the coming decades. Even with the expected improvements in agricultural yields and efficiency, there will be increasing demand for more agricultural land. However, expansion of agricultural land will lead to deforestation and increases in greenhouse gas emissions, loss of biodiversity and ecosystem services, and nutrient imbalances. To reduce these environmental impacts, a further increase in agricultural yields is needed, together with other options such as reduced food losses, dietary changes, improved livestock systems, and better nutrient management.

In the IMAGE framework, future development of the agricultural economy can be calculated using the agro-economic model MAGNET (formerly LEITAP; Woltjer et al. (2011)[26]; Woltjer et al. (2014)[27]). MAGNET is a computable general equilibrium (CGE) model that is connected via a soft link to the core model of IMAGE. Demographic changes and rising incomes are the primary driving factors of the MAGNET model, and lead to increasing and changing demand for all commodities including agricultural commodities. In response to changing demand, agricultural production is increasing, and the model also takes into account changing prices of production factors, resource availability and technological progress. In MAGNET, agricultural production supplies domestic markets, and other countries and regions are supplied via international trade, depending on historical trade balances, competitiveness (relative price developments), transport costs and trade policies. MAGNET uses information from IMAGE on land availability and suitability, and on changes in crop yields due to climate change and agricultural expansion on inhomogeneous land areas. The results from MAGNET on production and endogenous yield (management factor) are used in IMAGE to calculate spatially explicit land-use change, and the environmental impacts on carbon, nutrient and water cycles, biodiversity, and climate.

MAGNET is connected via a soft link to the core model of IMAGE. The MAGNET model is based on the standard GTAP model [28], which is a multi-regional, static, applied computable general equilibrium (CGE) model based on neoclassical microeconomic theory. Although the model covers the entire economy, there is a special focus on agricultural sectors. It is a further development of GTAP regarding land use, household consumption, livestock, food, feed and energy crop production, and emission reduction from deforestation.

Demand and supply

Household demand for agricultural products is calculated based on changes in income, income elasticities, preference shift, price elasticities, cross-price elasticities, and the commodity prices arising from changes in the supply side. Demand and supply are balanced via prices to reach equilibrium. Income elasticities for agricultural commodities are consistent with FAO estimates [29], and dynamically depend on purchasing power parity corrected GDP per capita. The supply of all commodities is modelled by an input--output structure that explicitly links the production of goods and services for final consumption via different processing stages back to primary products (crops and livestock products) and resources. At each production level, input of labour, capital, and intermediate input or resources (e.g., land) can be substituted for one another. For example, labour, capital and land are input factors in crop production, and substitution of these production factors is driven by changes in their relative prices. If the price of one input factor increases, it is substituted by other factors, following the price elasticity of substitution.

Regional aggregation and trade

MAGNET is flexible in its regional aggregation (129 regions). In linking with IMAGE, MAGNET distinguishes individual European countries and 22 large world regions, closely matching the regions in IMAGE (IMAGE regions). Similar to most other CGE models, MAGNET assumes that products traded internationally are differentiated according to country of origin. Thus, domestic and foreign products are not identical, but are imperfect substitutes [30].

Land use

In addition to the standard GTAP model, MAGNET includes a dynamic landsupply function [31] that accounts for the availability and suitability of land for agricultural use, based on information from IMAGE (see below). A nested land-use structure accounts for the differences in substitutability of the various types of land use [32][31]. In addition, MAGNET includes international and EU agricultural policies, such as production quota and export/import tariffs [33].

Livestock

MAGNET distinguishes the livestock commodities of beef and other ruminant meats, dairy cattle (grass- and crop-fed), and a category of other animals (e.g., chickens and pigs) that are primarily crop fed. Modelling the livestock sector includes different feedstuffs, such as feed crops, co-products from biofuels (oil cakes from rapeseedbased biofuel, or distillers grain from wheat-based biofuels), and grass [26]. Grass may be substituted by feed from crops for ruminants.

Land supply

In MAGNET, land supply is calculated using a land-supply curve that relates the area in use for agriculture to the land price. Total land supply includes all land that is potentially available for agriculture, where crop production is possible under soil and climatic conditions, and where no other restrictions apply such as urban or protected area designations. In the IMAGE model, total land supply for each region is obtained from potential crop productivity and land availability on a resolution of 5x5 arcminutes. The supply curve depends on total land supply, current agricultural area, current land price, and estimated price elasticity of land supply in the starting year. Recently, the earlier land supply curve [34] has been updated with a more detailed assessment of land resources and total land supply in IMAGE [35], and with literature data on current price elasticities. Regions differ with regard to the proportion of land in use, and with regard to change in land prices in relation to changes in agricultural land use. In regions where most of the area suitable for agriculture is in use, the price elasticity of land supply is small, with little expansion occurring at high price changes. In contrast, in regions with a large reserve of suitable agricultural land, such as Sub-Saharan Africa and some regions in South America, the price elasticity of land supply is larger, with expansion of agricultural land occurring at smaller price changes.

Reduced land availability

By restricting land supply in IMAGE and MAGNET, the models can assess scenarios with additional protected areas, or reduced emissions from deforestation and forest degradation (REDD). These areas are excluded from the land supply curve in MAGNET, leading to lower elasticities, less land-use change and higher prices, and are also excluded from the allocation of agricultural land in IMAGE [36].

Intensification of crop and pasture production

Crop and pasture yields in MAGNET may change as a result of the following four processes:

1. autonomous technological change (external scenario assumption);
2. intensification due to the substitution of production factors (endogenous);
3. climate change (from IMAGE);
4. change in agricultural area affecting crop yields (such as, decreasing average yields due to expansion into less suitable regions; from IMAGE). Biophysical yield effects due to climate and area changes are calculated by the IMAGE crop model and communicated to MAGNET. Likewise, also the potential yields and thus the yield gap can be assessed with the crop model in IMAGE. External assumptions on autonomous technological changes are mostly based on FAO projections [37], which describe, per region and commodity, the assumed future changes in yields for a wide range of crop types. In MAGNET, the biophysical yield changes are combined with the autonomous technological change to give the total exogenous yield change. In addition, during the simulation period, MAGNET calculates an endogenous intensification as a result of price-driven substitution between labour, land and capital. In IMAGE, regional yield changes due to autonomous technological change and endogenous intensification according to MAGNET are used in the spatially explicit allocation of land use.

Technology change in agriculture

The management factor (MF) describes the actual yield per crop group and per socio-economic region as a proportion of the maximum potential yield. This maximum potential yield is estimated taking into account inhomogeneous soil and climate data across grid cells. The MF for the period up to 2005 is estimated as part of the IMAGE calibration procedure, using FAO statistics on actual crop yields and crop areas [38]. The start year for the MF is subsequently taken as point of departure for future projections.

Guidance for future development of yield changes is provided by expert projection such as the assumptions in FAO projections up to 2030 and 2050 [39][37].The FAO trends are used as exogenous technical development in the MAGNET model, and subsequently adjusted to reflect the relative shortage of suitable land, as part of the model calculation. The combinations of production volumes and land areas from MAGNET are adopted as future MF projections into the future in IMAGE.

Future technological change is dependent on the storyline and needs to be consistent with other scenario drivers. For instance, strong economic growth is typically facilitated by rapid technology development and deployment, rising wages and a labour shift from primary production (agriculture) to secondary (industry) and tertiary (services) sectors. These developments foster more advanced management and technology in agriculture. In order to reflect different trends in exogenous yield increase, FAO trends are combined with projections of economic growth to develop scenario-specific trends of yield changes in multiple-baseline studies, like for the SSPs. Because the MF is such a decisive factor in future net agricultural land area, careful consideration of uncertainties is warranted.

5.2) Forestry - IMAGE

The forest management module describes regional timber demand and the production of timber in the three different management systems clear felling, selective felling and forest plantations. Deforestation rates reported by FAO are used to calibrate deforestation rates in IMAGE, using a so called additional deforestion.

Timber demand

In IMAGE 3.0, the driver for forest harvest is timber demand per region. Timber demand is the sum of domestic and/or regional demand and timber claims by other regions (export/trade). Production and trade assumptions for saw logs and paper/pulp wood are adopted from external models, such as EFI-GTM [40], and domestic demand for fuelwood is based on the TIMER model. Part of the global energy supply is met by fuelwood and charcoal, in particular in less developed world regions. Not all wood involved is produced from formal forestry activities, as it is also collected from non-forest areas, for example from thinning orchards and along roadsides [41][42]. As few reliable data are available on fuelwood production, own assumptions have been made in IMAGE. While fuelwood production in industrialized regions is dominated by large-scale, commercial operations, in transitional and developing regions smaller proportions of fuelwood volumes are assumed to come from forestry operations: 50% and 32% respectively.

Timber supply & production in forests

In IMAGE, felling in each region follows a stepwise procedure until timber demand is met, attributed to the three aforementioned management systems. The proportion for each management system is derived from forest inventories for different world regions [43] and used as model input. Firstly, timber from forest plantations at the end of their rotation cycle is harvested. Secondly, trees from natural forests are harvested, applying clear felling and/or selective felling. In all management systems, trees can only be harvested when the rotation cycle of forest regrowth has been completed.

Selective logging: Under selective felling, only a regional and time specific fraction of the trees is logged and the other trees remain in the forest. After logging, a fraction of the harvested wood is removed from the forest to fulfil the demand. Biomass left behind in the forest represents losses/residues during tree harvesting (from tree damage and unusable tree parts) or left in the forest because of environmental concerns (biodiversity and nutrient supply). The fraction take-away is derived from literature, defined for industrial roundwood [43]. It is further adjusted to account for the demand for wood fuel, for which it equals unity.

Forest plantations: Forest plantations are established for efficient, commercially viable wood production. Their regional establishment in IMAGE 3.0 is scenario driven, based on FAO. The expectation is that increasingly more wood will be produced in plantations because sustainability criteria may limit harvest from natural forests [44][45][46]. The development of forest plantations in IMAGE and LPJmL is still under development, but expected to be available soon. Forest plantations are assumed to be established firstly on abandoned agricultural land. When sufficient abandoned land is not available, forest plantations are established on cleared forest areas. When a forest plantation has been established, the land cannot be used for other purposes or converted to natural vegetation until the tree rotation cycle has been completed.

Additional deforestation

Globally, conversion to agricultural land is the major driver of forest clearing, and timber harvest does not result in deforestation, if natural vegetation is regrowing. But there are other causes of deforestation not related to food demand and timber production, such as urbanisation, mining and illegal logging. These activities contribute to loss of forest area, increased degradation risks and a decline in the supply of forest services. To be consistent with the total deforestation rates per world region reported by the FAO [47], IMAGE 3.0 introduces a category additional deforestation. IMAGE assumes no recovery of natural vegetation in these areas, and no agricultural activities.

5.4) Bioenergy land-use - IMAGE

MAGNET includes ethanol and biodiesel as first-generation biofuels made from wheat, sugar cane, maize, and oilseeds [48] and the use of by-products (DDGS, oilcakes) from biofuel production in the livestock sector.

For more information, see the Energy resource endowments - IMAGE.

5.5) Other land-use - IMAGE

LPJmL is a Dynamic Global Vegetation Model (DGVM) that was developed initially to assess the role of the terrestrial biosphere in the global carbon cycle [49]. DGVMs simulate vegetation distribution and dynamics, using the concept of multiple plant functional types (PFTs) differentiated according to their bioclimatic (e.g. temperature requirement), physiological, morphological, and phenological (e.g. growing season) attributes, and competition for resources (light and water).

To aggregate the vast diversity of plant species worldwide, with respect to major differences relevant to the carbon cycle, LPJmL distinguishes nine plant functional types. These include e.g. tropical evergreen trees, temperate deciduous broad-leaved trees and C3 herbaceous plants. Plant dynamics are computed for each PFT present in a grid cell. As IMAGE uses the concept of biomes (natural land cover types), combinations of PFTs in an area/grid cell are translated into a natural land cover (biome) type (see Plant functional types and natural land cover types).

6) Emissions - IMAGE

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. On this page the general approaches to projecting emissions in the IMAGE framework are described for modelling 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). The methods used for modelling both GHGs emissions, pollutants, and non-GHG forcing agents are very similar and therefore described together. On the GHGs page the modelling of emission abatement is described.

An overview of the emissions model structure is provided in Figure 10.

General approaches

Air pollution and GHG emission sources included in IMAGE are listed in Table 5. 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.

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. The equation for this emission factor approach is:

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

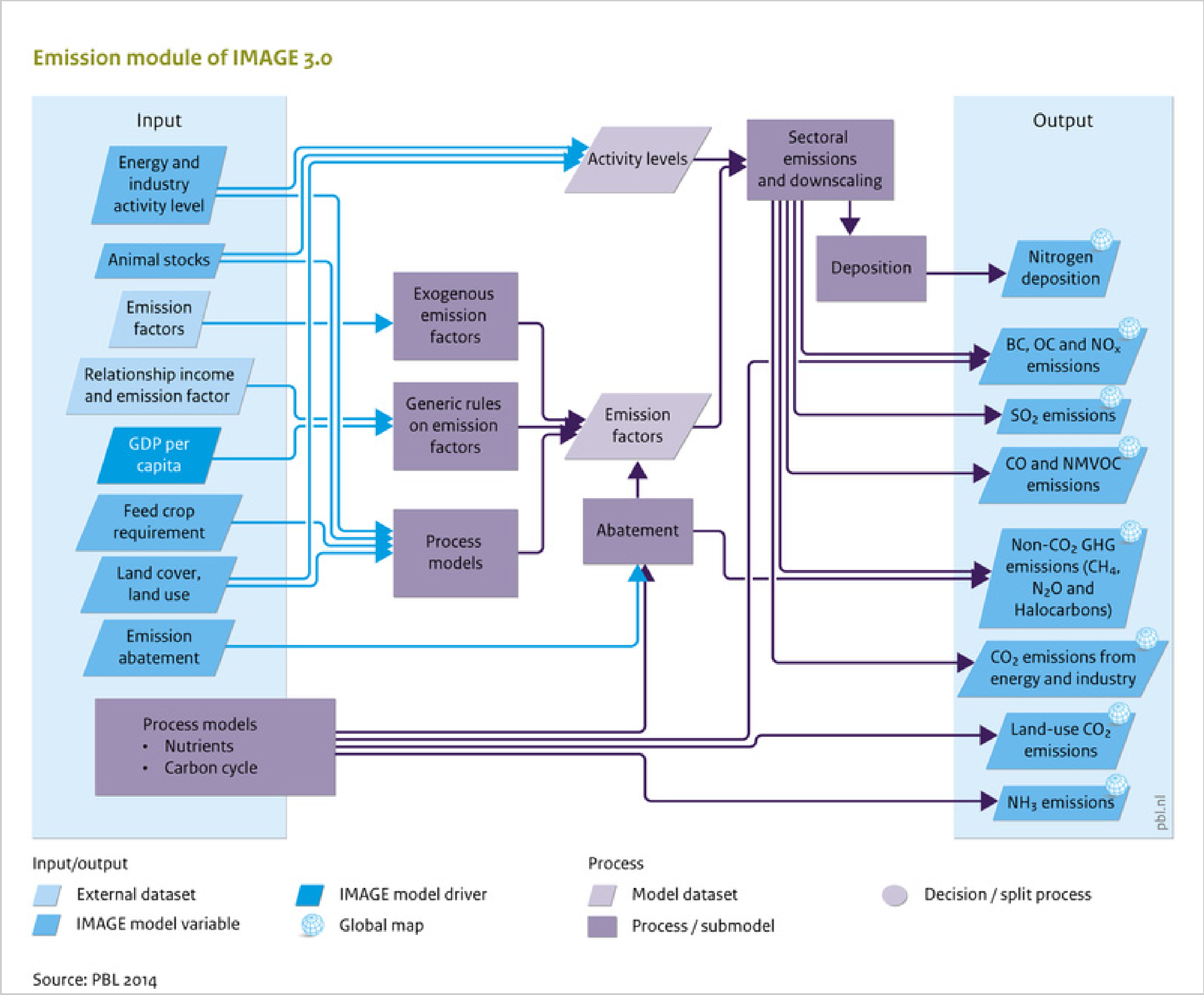


Figure 10: Flowchart Emissions module.

- i is the index for further specification (sector, energy carrier)
- EF-base is the emission factor in the baseline
- and 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 the equation, 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).

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

GEF is a special case of the EF method, where the activity is grid-specific, resulting in grid-specific emissions. This is done for a number of sources, such as emissions from livestock.

4) *Gridded model (GM)*

Land-use related emissions of NH_3, N_2O and NO are calculated with grid-specific models. The models included in IMAGE are simple regression models that generate an emission factor. For comparison with other models, IMAGE also includes the N_2O methodology generally proposed by IPCC [50].

Table 5: Atmospheric emissions calculated in IMAGE, by source and by method applied

Source	Activity	CO_2	CH_4	N_2O	SO_2	NO_x	CO	NMVOC	F-gases	BC	OC	NH_3
a). Energy related												
End-use energy use (industry, transport, residential, services and other)	Energy consumption rates	EF	EF	EF	EF	EF	EF	EF		EF	EF	
Energy sector (production of power, hydrogen, coal, oil, gas, bioenergy)	Energy prodcution rates	EF	EF	EF	EF	EF	EF	EF		EF	EF	
Energy transport	Energy transport rates		EF									
Other energy conversion	Energy conversion rates	EF	EF	EF	EF	EF	EF	EF		EF	EF	
b). Industry related												
Emissions from industrial process	Industry value added (IVA)	EF	EF	EF	EF	EF	EF	EF	EF	EF	EF	
Cement and Steel	Regional production	EF										
c). Agriculture-, waste-, and land-use related												
Enteric fermentation, cattle	Feed type and amount		GM[a]									
Animal water, all animal categories	Number of animals		GEF	GEF		GEF						GEF[b]
Enteric fermentation, cattle	Feed type and amount		GM[a]									
Landfills	Population		GEF									
Enteric fermentation, cattle	Feed type and amount		GM[a]									
Deforestation	Carbon burnt	GM	GEF	GEF	GEF	GEF	GEF	GEF		GEF	GEF	GEF
Agriculture waste burning	Carbon burnt	GM	GEF	GEF	GEF	GEF	GEF	GEF		GEF	GEF	GEF
Traditional biomass burning	Carbon burnt	GM	GEF	GEF	GEF	GEF	GEF	GEF		GEF	GEF	GEF
Savannah burning	Carbon burnt	GM	GEF	GEF	GEF	GEF	GEF	GEF		GEF	GEF	GEF
Domestic sewage treatment	Population, GDP		GEF	GEF								
Wetland rice field	Area wetland rice		GEF									
Crops	N fertiliser and manure input, croptype			GM		GM						GM
Managed grassland	N fertiliser and manure input			GM		GM						GM
Indirect emissions	N crops, fertiliser and manure input			GM								
Land-use change	Clearing forest areas			GM								
d). Natural sources												
Soils under natural vegetation	Net primary production			GM		GM						GEF
Natural vegetation	N/A						W	W				
Wildfires	N/A		W				W					
Oceans	N/A		W	W			W					W
Natural wetlands	N/A		W									

Termites	N/A		W									
Wild animals	N/A		W									
Methane hydrates	N/A		W									
Volcanoes	N/A		W		W							
Lightning	N/A			W		W						

Activity describes the activity level to which the emission factor is applies, or, if only GM method occurs, the main determinant for the gridded model.

Methods:

- W=Global emission
- EF=Regional emission factor applied to the specified activity level
- GEF=Grid-specific emission calculated from gridded activity level and (regional) emission factor
- GM= Gridded, model-based emission (statistical or process-based model).

Footnotes:

[a] *GM for dairy and non-dairy cattle, EF for other animal categories.*

[b] *EF for NH_3 emissions from animal houses, manure storage and grazing livestock;GM for NH_3 emissions from manure spreading.*

Emissions from energy production and use

Emission factors are used for estimating emissions from the energy-related sources. In general, the Tier 1 approach from IPCC guidelines [50] 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 [51]. 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)[52]. 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 ([53][54][55] [56][57]). 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.

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 (See Industrial sector page). 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)[58], which derived relationships with income for the main uses of halogenated gases (HFCs, PFCs, SF6). In the actual use of the model, slightly updated parameters are used to better represent the projections as presented by Velders et al. (2009)[59]. The marginal abatement cost curve per gas still follows the methodology described by Harnisch et al. (2009)[58].

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, N2O), 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 is used (Equation 1). 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. 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 [50] 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.

6.1) GHGs - IMAGE

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 by comparing the costs of non-CO_2 abatement in agriculture and other mitigation options.

7) Climate - IMAGE

Climate model MAGICC

IMAGE uses the simple climate model MAGICC 6.0 [60][61], which was developed by developed by the MAGICC 6 group (link (http://wiki.magicc.org/index.php?title=MAGICC_team%7Csee)) to simulate the effects of changing greenhouse gas emissions on atmospheric composition, radiative forcing and global mean temperature. MAGICC calculates atmospheric CO_2 concentration based on CO_2 emission data for energy, industry and land-use change; terrestrial carbon balance; and carbon uptake by the oceans (calculated in MAGICC on the basis of the Bern Ocean Carbon model).

Concentrations of other long-lived greenhouse gases (CH_4, N_2O, and halocarbons), and tropospheric ozone (O_3) precursors (CO, NMVOC) are calculated by MAGICC in a simple atmospheric chemistry module. Halocarbons and N_2O concentrations mostly show a simple mass-concentration conversion and half-life behaviour. CH_4 and ozone dynamics are more complex, with CH_4 lifetime depending on the OH concentration level, and O_3 and OH concentration levels depending on CH_4

concentrations, and NO_X, CO and NMVOC emissions [61].

MAGICC was used extensively in the Third, Fourth, and Fifth assessment reports of IPCC (Intergovernmental Panel on Climate Change) in assessing a range of greenhouse gas concentration scenarios. Since publication of these reports, MAGICC has been updated in line with results from Atmosphere-Ocean General Circulation Models (AOGCMs).

There is still considerable uncertainty in climate change simulations, as illustrated by differences in results from various AOGCMs, in terms of mean global temperature, and even more so in geographical patterns of surface temperature and precipitation. By adjusting the values of a few of the model parameters, MAGICC 6.0 can reproduce timedependent responses of AOGCMs [60][61]. This allows IMAGE to reflect the uncertainty in AOGCM results, and to provide plausible projections of future climate-change feedbacks and impacts.

The analysis of climate impacts and feedbacks requires location-specific temperature and precipitation changes. Thus, a pattern scaling technique is applied in IMAGE by combining MAGICC results with maps on climate change from the same AOGCMs assessed in AR4 [62] and used for calibrating MAGICC. The consistent combination of AOGCM-specific parameter settings for MAGICC and matching geographical patterns of climate change make the dynamic results from IMAGE physically more consistent, and extend the range of uncertainties that can be covered to include future climate change.

7.1) Modelling of climate indicators - IMAGE

Change in atmospheric gas concentrations also changes the amount of radiation absorbed or transmitted by the atmosphere, and thus changes the earth's energy balance and temperature. The energy balance change is expressed as radiative forcing per gas, measured in W/m^2. In MAGICC, concentrations of long-lived greenhouse gases are translated into radiative forcing values using radiative efficiency estimates from the IPCC [63], and radiative forcing of tropospheric ozone is calculated based on ozone sensitivity factors from MAGICC 6.0 [60][61].

However, other processes also lead to changes in the atmospheric energy balance, which are also modelled and assigned a radiative forcing value. Aerosols, such as SO_2, NO_X, and organic carbon, have a direct cooling effect by reflecting more radiation back into space (direct aerosol effect). They also interact with clouds and precipitation in many ways (indirect aerosol effect); this cloud feedback is the largest source of uncertainty in estimating climate sensitivity [64]. Although also an aerosol, black carbon has a strong direct warming effect [65].

Direct and indirect aerosol effects are approximated in MAGICC by scaling the radiative forcing in a reference year (mostly 2005) with the relative increase in future emissions with respect to emissions in the reference year. As MAGICC assumes radiative forcing by albedo and mineral dust to stay constant over the scenario period [60], this is also assumed in IMAGE.

8) Non-climate sustainability dimension - IMAGE

IMAGE 3.0 modules for the Human system and Earth system are closely linked via multiple feedback mechanisms to form the core model of IMAGE 3.0. These modules produce output for two types of purposes. One purpose is to serve as input for other IMAGE modules and the other purpose is to serves as indicator for impacts. Many outputs serve both purposes, and many state variables of the IMAGE core modules constitute interesting impact indicators, such as land-use change, crop yields and climate parameters.

The range of impacts has been extended beyond those that the core model can provide. As a result, additional impact modules have been developed and linked to the IMAGE core model through static data exchange. These impact modules can be used to address specific interests, and have been used in exploring a broad range of interactions between issues in sustainable development. Impact components available in the IMAGE 3.0 framework include Terrestrial and Aquatic biodiversity, Flood risks, Land degradation, Ecosystem services, and Human development. For more information on the impact modules visit the IMAGE 3.0 website (http://themasites.pbl.nl/models/image/index.php/Impacts).

10) References - IMAGE

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