PBL Netherlands Environmental Assessment Agency

THE IMAGE STRATEGY DOCUMENT 2022-2027

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November 2021

PBL

Colophon

The IMAGE Strategy Document 2022-2027

The Hague, 2023
PBL publication number: 4741

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Contents

Summary

This document describes the priority areas in the IMAGE strategy in the period 2022-2027. These priorities are grouped into relevance for salience, legitimacy and credibility. The actual activities will be further elaborated in the annual and multi-year programmes and the project activities funded by external parties.

Table S.1
Critical priority areas and continuous activities with related paragraph numbers

Salience	**Legitimacy**	**Credibility**
4.1.1 Identifying strategies to reach sustainable development goals	4.2.1 Developing and implementing the IMAGE open science strategy	4.3.1 Developing more efficient methods for model use
4.1.2 Identifying strategies to reach net-zero emission systems	4.2.2 Better representation of response strategies and policies	4.3.2 Model language
4.1.3 Representing circular economy and material flows	2.3.4 Focus on missing links between issues	4.3.3 Other methodological improvements in IMAGE-energy
4.1.4 Reconciling multiple land claims	5.1 Quality assurance plan	4.3.4 Other methodological improvements in IMAGE-land
		4.3.5 Other methodological improvements in IMAGE-integration
	Regular contact with Advisory Board and clients. Active presentation of results	Publication in science journals. Regular contact with Advisory board

The document also indicates several critical organisational issues related to cooperation and functioning of the team.

FULL RESULTS

1 Introduction

The IMAGE integrated assessment modelling framework has been developed at PBL Netherlands Environmental Assessment Agency (and its predecessors) since the late 1980s (Rotmans, 1990). Originally, the model focused specifically on climate change. In the early 1990s, it was used with the ASF model (USA) to develop the first set of IPCC scenarios (Van Beek, 2020). Over time, the model's coverage became increasingly comprehensive to describe the drivers of climate change better, adding detailed representations of energy and land use, changes in the biosphere, and emissions of greenhouse gases and air pollutants. As a result, the model also became capable of analysing other environmental problems than climate change. IMAGE projections, for instance, formed the backbone of UNEP's first Global Environmental Outlook (UNEP, 1997). This shift in focus was reflected in the name change from *Integrated Model to Assess the Greenhouse Effect* to *Integrated Model to Assess the Global Environment.* Moreover, the model has also increasingly been used to look at the even wider notion of sustainable development (e.g., the Roads from Rio publication in 2012 (Van Vuuren, 2012)). Since then, the model has been further developed and used in developing scenarios for climate change, biodiversity loss, environmental problems, and nitrogen pollution (see also Box 2.1). The latest version of the IMAGE model, IMAGE 3.2, was released in 2020 (see also (Van Vuuren, 2021)). The model version is documented on the wiki-based model documentation[1].

This document describes the **research and development strategy for the 2022-2027 period**, based on understanding the main research questions for the next few years. It succeeds the earlier document for the 2015-2020 period. The main aim is to provide **a vision with a clear ambition and direction** for the coming years, to which the various research activities connect and contribute. The vision will be elaborated in the IMAGE project as part of the PBL annual work programme and externally funded projections, building on this strategy document. Similarly, the multi-year PBL programmes International Climate Policy and Global Environmental Change will help ensure this document's implementation. This also means, given available budget, opportunities and other developments, that there will be (some) flexibility in implementation in practice.

The core of the IMAGE model (mostly dealing with land-use/land cover, energy, climate and the earth environmental system) has over time been used in combination with a growing set of models and analysis tools within PBL. The complete set of coupled models is referred to as the IMAGE framework. The main coupled models include the biodiversity model GLOBIO, the GISMO development model, and the nutrient model GNM. This strategy focuses on the core IMAGE model itself, but in the context of the larger framework. Development strategies for other components of the framework (e.g., GLOBIO) are elaborated in separate strategic documents.

[1] https://models.pbl.nl/image/index.php/Welcome_to_IMAGE_3.2_Documentation

This strategy document was developed during a process of about one year that consisted of the following steps (a more detailed description is provided in Chapter 3):

- Discussion among IMAGE team members
- Brainstorm discussions with the IMAGE Advisory Board
- Alignment of the document with strategic documents of PBL and its Department of Climate, Air and Energy (KLE)
- Consultation of the sectors NLG and WLV

As part of the strategy, this document provides an answer to the following questions:

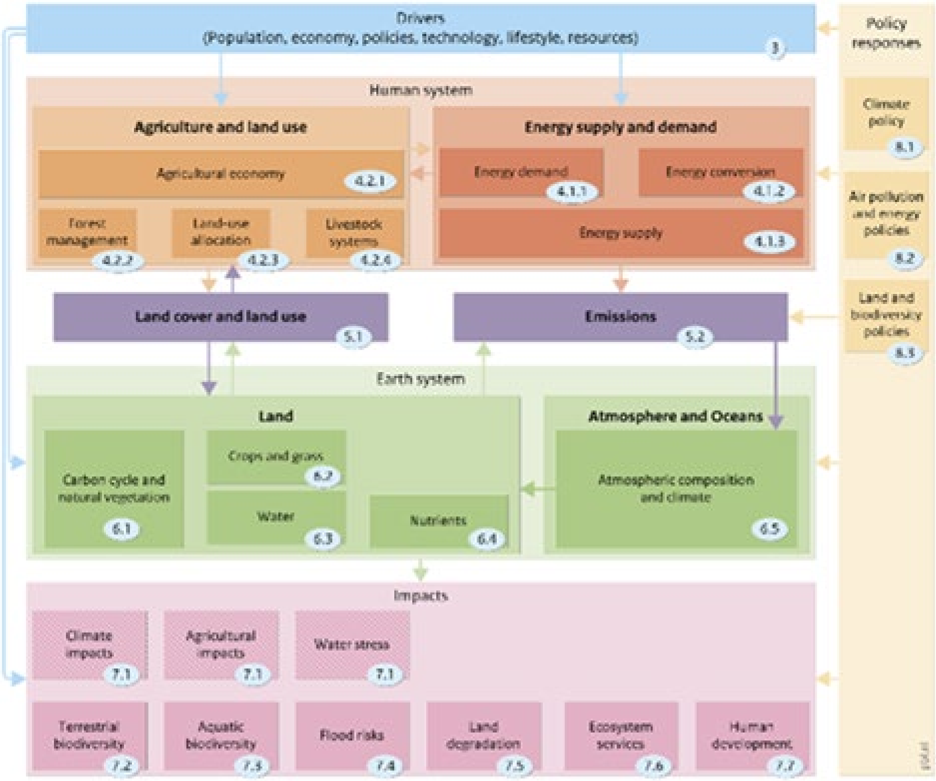
- ***What is the current status of the model?*** What are the current strengths and limitations of the IMAGE model? (***Chapter 2***)
- ***What are key questions and priorities for IMAGE development?*** What policy questions will arise over the next five years? What questions do we want or need to answer using the IMAGE model? Who will be our main clients? (***Chapter 3***)
- ***What are critical focus areas for analysis and model development?*** Given this question and the current status of the model, what should be the focus of research and model development over the next five years? (***Chapter 4***)
- ***How can this strategy be implemented and what is the organisation strategy?*** How should the IMAGE work be organised in practical terms? Are there consequences for the infrastructure and quality management? (***Chapter 5***)

2 Current status of the model

2.1 Introduction of IMAGE

IMAGE is an integrated assessment model framework that simulates the environmental consequences of human activities and development and, to some degree, the impact of environmental change back on human development. It thus forms part of a family of models called integrated assessment models (IAMs). IAMs describe the interactions between society, the biosphere, and the climate system to assess sustainability issues such as climate change, biodiversity and human wellbeing. The model aims to keep track of complicated relationships between different parameters both in time and across scales. Given all uncertainties (including human decisions), IMAGE - like other IAMs - does not aim to predict the future but instead explore possible outcomes under different assumptions - showing possible relevant considerations for decisions today.

Figure 2.1
The IMAGE 3 modelling framework (numbers refer to chapters in the IMAGE 3.0 model documentation) (Stehfest, 2014)



The main structure of the IMAGE-3 model is indicated in Figure 2.1. For the human system, key components of the model are the energy (TIMER) and agriculture/land use system (MAGNET and IMAGE-Land). Important drivers of these systems are demographic and economic development, technology development, lifestyle change and policy. Some are exogenous to the IMAGE system (e.g., population and economic growth), while others are explicitly modelled (technology, resource availability). IMAGE describes land cover, growth of biomass, nutrient and water cycle, and climate as part of the earth system, using mostly the LPJml and MAGICC models. Key interactions between the human and earth system are emissions and land use. Subsequently, it is possible to describe critical impacts of changes in the human and earth system for environmental parameters and human development. Most parameters in the human system are described at the level of 26 world regions. The earth system is described mostly at 5x5 minute and 0.5 x 0.5-degree grid.

Box 2.1 History of the IMAGE model

In terms of the history of the model, various phases can be identified:

- IMAGE 1.0. Single-region, global model focused on the climate change problem. Identification of relevant long-term dynamics (Rotmans, 1990)
- IMAGE 2.0. Geographically explicit model: 0.5 x 0.5 grid for the natural system and 13 model regions. Focus on the climate change problem, but with a detailed land-use/landcover system (Alcamo, 1995)
- Parallel development of TARGETS 1.0. A global model aimed at an integrated representation of various human and system components to study sustainable development (Rotmans, 1997)
- IMAGE 2.1–2.4. Geographically explicit model. 0.5 x 0.5 grid for the natural system and 18 to 26 model regions. Focus on broader environmental change. More comprehensive coverage of the energy system. Active participation in many international assessments (Alcamo, 1998, Leemans, 1999, IMAGE-team, 2001, Bouwman, 2006)
- IMAGE 3.0. Further development of the IMAGE system by including new elements for the biosphere, carbon cycle, land allocation, and water and a more detailed representation of the energy system, especially for energy demand (Stehfest, 2014)
- IMAGE 3.2. Improvements in energy demand, energy supply and land use modelling, including a detailed representation of industrial energy use, service sector energy use, the addition of several new crop types and more land-based mitigation options. The model has been calibrated to 2015 and, where possible, 2020 (Van Vuuren, 2021)

2.2 Position of IMAGE, including strengths and limitations

2.2.1 Integrated assessment models

Several types of models are used for analysing global environmental change and human development issues. Given the complexity of the issues at stake, these models have chosen different strategies for dealing with them. Based on this strategy and the aim of the model, this is mostly about finding the right balance between transparency, complexity and simplification. Various groups of models relevant for global environmental change research can be identified concerning these strategies:

Earth system models, in general, describe the full complexity of earth system processes intending to further scientific understanding (and with strong simplification of the human system). *Macroeconomic models*, in contrast, focus mostly on the representation of economic consequences for the near term (detailed analysis of economic impacts of environmental policies, combined with simplification of the interaction with the earth system.
Integrated assessment models provide a balanced representation of both earth and human systems to describe their interaction.

The main characteristics of IAM models, including IMAGE, are:

- **Simplification** (focus on meta-relationships).
- **Integration** (focus on the relationship between various topics; in particular between the earth and the human system)
- **Policy relevance** (IAMs support policy decisions).

Most IAMs focus on long-term processes of both earth and human systems (e.g., technology change, changes in consumption patterns, environmental degradation). Different classes can be identified within the group of IAMs, although the models also have so many individual characteristics that there is a strong overlap between these models:

i. *Cost-benefit analysis models* (e.g., FUND, MERGE, DICE). These models provide a full-circle representation of environmental change; while human activities lead to environmental degradation, such degradation also leads to economic damages. While these models, thus, are highly integrated, they combine this integration with a large degree of simplification of both human and earth systems to remain sufficiently transparent.
ii. *Energy system models with climate system representation* (TIAM). This category includes energy optimisation models that are coupled to a climate system. To some degree, some of the larger IAM models also originate from this category.
iii. *Process-oriented energy/land IAM frameworks (MESSAGE/GLOBIOM, REMIND/MAGPIE, AIM, GCAM, IMAGE)*. These models apply an intermediate complexity representation of the human system (economy, energy, and land use) and the earth system (climate, land cover and biogeochemical cycles) to describe the relevant processes of climate change and global environmental change.

2.2.2 Characteristics of IMAGE as an integrated assessment model

IMAGE represents a process oriented IAM. IMAGE can be regarded as one of the models pioneering this approach - being the first land/energy coupled model with a climate representation. The model structure (Figure 2.1) shows that IMAGE covers a wide range of topics in both the human and earth system and their interactions. Compared to many other IAMs, the IMAGE model also has a very high resolution: it describes socio-economic processes for 26 world regions and most environmental parameters at a 5x5 or 30x30 minute grid. On a temporal scale, the model operates mostly on a one-year step resolution. The resolution is also high in terms of consumer classes, energy technologies and crop categories. The strengths and limitations of the IMAGE framework can also be compared to those of other IAMs. Several of these 'limitations' simply result from the modelling philosophy and strategy and are, therefore, not necessarily areas for improvement. It should be noted that models should not become 'models of everything' to avoid them becoming too complex and losing focus. In that sense, it is useful to see the position of IMAGE within the context of a wider set of models in the field of global environmental change assessment.

Compared to other integrated assessment models, the IMAGE approach can be summarised as follows:

- **Strong focus on representing both the earth and human systems in terms of physical indicators.** The advantage is that this allows for an easier link with the drivers of environmental degradation and a meaningful representation of long-term dynamics. As a result, also **human activities** are preferably represented in terms of **physical units** (e.g., number of cows) than in terms of monetary units.
- IMAGE is a **simulation model** (not an optimisation model), making it specifically suitable for exploring the full range of scenario analyses.
- IMAGE contains a **balanced representation of the land-use/agricultural system and the energy system.** The team also has a long tradition of coupling these two systems.
- The IMAGE model contains a **detailed representation** of the variables useful in environmental assessments (e.g., emissions, land use, energy system).
- A key component of the IMAGE model is its **geographical detail.** It represents the human system for many regions and includes a detailed grid for environmental system calculations.

The IMAGE modelling framework also has certain limitations, namely:

- Not all sub-models of IMAGE contain an explicit representation of policy measures. This is, for instance, the case for emissions (modelled via abstract emission factors) and agricultural yields (modelled via an abstract management factor). To describe the feasibility of policy responses, it is useful to be more explicit about underlying processes. This is the case for several other areas (e.g., energy supply and demand; or food trade). In the areas where more abstract factors are used, it might still be possible to evaluate response strategies by linking the factors to real-world situations and/or model improvement.
- There is limited feedback from the environmental system to the socio-economic system. For example, there is no feedback on population growth or economic growth assumptions.
- Not all of the main linkages between the various issues are included. For example, there is no feedback from water scarcity to energy decisions.
- Some IMAGE sub-models form part of one large model code, implying that they can exchange information in every time step. In contrast, others are coupled via the exchange of data files (e.g., the way TIMER and MAGNET are coupled to the other models in the IMAGE framework). This provides more flexibility – but is also riskier in terms of model management and limits the ability to take any feedback into account.
- The IMAGE model has a limited representation of short-term macroeconomic dynamics. Currently, price responses are represented in the energy system model, but any feedback on economic structure, for instance, is lacking. Economic feedback is described in the coupled MAGNET (agro-economic model).

- IMAGE is a simulation model: Policy optimisation, therefore, is normally done by using methods that run the model interactively multiple times, evaluating the outcomes based on pre-set criteria.
- Not all possible biophysical feedbacks are represented in the model. In particular, certain very local feedback (e.g., concerning the land/water/energy nexus; or aerosol/climate interactions) or feedbacks that involves more complex mechanisms (certain atmospheric chemistry representations) are difficult to describe in IAMs.
- The representation of policies in different areas of the model can be further improved. This includes building standards or the impact of using different fertiliser levels. In this area, considerable progress has been made in the 2015-2020 period.
- Like other IAMs, the focus is mostly on technology and economic considerations. Still, the IMAGE-team has paid quite some attention to work with, among others, researchers working on lifestyle change and transition sciences to ensure input in scenario development - but these are not represented directly in the model code.

2.3 Key developments in the period 2015-2020

The IMAGE model's history goes back to 1988. Since then, the model has been applied and further developed. In 2014, the IMAGE-3 version was released and presented to the Advisory Board. Below we provide a brief overview of some key developments in the period 2015-2020.

2.3.1 Strategy 2015-2020

In the strategy for the IMAGE model development for 2015-2020, three focus questions were formulated (Van Vuuren, 2015):

- What are effective response strategies to deal with climate change?
- What strategies could provide sufficient food for 9 billion people by 2050 while conserving biodiversity and providing ecosystem goods and services?
- What strategies could implement multiple sustainable development objectives (SDGs/Planetary Boundaries) simultaneously?

Moreover, several priorities were formulated for model development that would allow better answering the three focus questions:

- Further attention to modelling response strategies.
- Further attention to implications of global environmental change for human development
- Further attention to integration
- Further attention to uncertainty.

In the following sections, we discuss the progress of the IMAGE team in the 2015-2020 period in terms of model application, model development, and development of the IMAGE team.

2.3.2 Model application

Key outputs of the IMAGE team include the contribution to global assessments, publications in scientific journals and direct policy support. It should be noted that publications in scientific journals are important to enhance credibility and support the two other forms of output: most assessments mainly use the information published in the peer-reviewed literature.

Global Environmental Assessments

In the 2015-2020 period, the IMAGE team contributed to several key scenario assessments. First of all, the team directly contributed to developing the Shared Socio-economic Pathways (SSPs) and the SSP-derived mitigation scenarios. The team developed the SSP1 marker scenario and elaborated on the other SSPs. The team also took a leading role in developing the SSP concepts and encouraging their use in CMIP6. The SSPs and the CMIP6 elaborations form a key input into the 2021/2022 IPCC assessments. The IMAGE scenarios, as a result, were clearly visible in the IPCC Special Reports on 1.5 degree and land and the upcoming Sixth Assessment Report. IMAGE also played a major role in the Global Land Outlook1 and 2 (GLO), for which it formed the key scenario input. The IMAGE-GLO scenarios were based on the SSPs (to allow the link to other assessments) but were elaborated more on the consequences of land-use change and land degradation. The GLO supports the Convention to Combat Desertification (CCD). In addition, the IMAGE model was also used in several different key assessment reports, including the UNEP's Global Environmental Outlook (GEO5/GEO6), the subsequent reports of The World in 2050 (TWI2050) (sustainable development) and the IPBES report on biodiversity. Several other assessments used IMAGE information, including 'The geography of future water challenges' (water) and the assessment work on nitrogen pollution as part of the INMS project. The contribution of IMAGE to Global Environmental Assessments is summarised in Table 2.1.

Table 2.1
Overview of IMAGE contributions to Global Environmental Assessments, organised by the IMAGE focus questions

Question	Assessments	Role
What are effective strategies to combat climate change?	IPCC-SR1.5, IPCC-SRLand, IPCC-AR6	IMAGE scenarios are used as part of the scenario database, or more explicitly, as Illustrative Pathway. IMAGE scenarios are also used in the UNEP Gap reports. Various IMAGE members are authors of the IPCC reports and the UNEP gap report.
What are strategies that can combine ensuring food security while preserving biodiversity and ecosystem services?	Global Land Outlook	IMAGE scenarios form a key input for analysis in GLO-1 and the upcoming GLO-2, focusing on risks for land degradation (https://www.pbl.nl/en/publications/exploring-future-changes-in-landuse) and potentials for restoration (Van der Esch, 2021)
	IPBES	IMAGE scenarios are used in combination with their evaluation by biodiversity models.

Question	Assessments	Role
What strategies can implement sustainable development objectives?	UNEP GEO5/GEO6	IMAGE scenarios formed input for describing sustainable development pathways
	The World in 2050	IMAGE scenarios formed input for describing sustainable development pathways

Direct policy support

IMAGE was used to support policymaking in various areas directly. The model was used directly in projects funded by national or European policymakers and contributed more indirectly to policymaking via several research projects funded by the European Research Councils (Horizon-2020). An overview is provided in Table 2.2. Similarly, the model also contributed to direct policy analysis for the Netherlands' government and the European Commission.

Table 2.2
Overview of key external projects

Organisation/Project	Topic	Project
EU Horizon-2020	Climate-policy focus	CD-LINKS, ENGAGE, COACCH, CRESCENDO, SENTINEL, ECEMF
	Land use, nexus	LUC4C, SIM4NEXUS
	SD focus	PICASSO, SHAPE
	Model focus	NAVIGATE
European Commission (directly for DGs)	Climate policy	COMMIT, PBL-Climate
	Land use	AgClim
Netherlands' Government	Climate policy	Model results of the IMAGE model are regularly presented or used in PBL publications.
	Development policy	IMAGE contributes to a large project from PBL to support strategic thinking at DGIS.
UK Government	Climate policy	Several projects for BEIS
Other	Behaviour	KR-Foundation (executed by UU)
	Climate policy	Several projects funded by the IKEA foundations (executed by UU)

The projects funded by the European Research Council (Horizon-2020) have provided a major source of funding for the IMAGE team and provided an opportunity for policy-relevant work. The work of several projects was cited in impact assessments as part of European policy initiatives or in the policy-relevant assessments discussed in the previous section.

Another example of model application is the COMMIT project. Here, the IMAGE team worked with other IAM teams directly with policymakers to develop scenarios that show the impact of current climate policies and pathways to strengthen them (good practice policies scenarios). The results are also presented in the so-called stocktake tool (interactive website).

IMAGE was also used in specific studies - among others on short-lived climate forcers (EMF33), bioenergy (EMF30), food security (AgMIP) and protection of biodiversity (Bending the Curve). Overall, the IMAGE team is aiming to broaden model applications in different areas. The work for the Ministry of Foreign Affairs, for instance, includes a focus on different pathways to increase energy access and its implications. In PICASSO, SHAPE and SIM4NEXUS, we are further widening the focus to a wider set of sustainability issues.

Scientific publications

Together, the various applications have also led to scientific publications. Over the 2015-2021 period, the team published around 40 papers per year, ensuring the scientific quality of the work. Increasingly, the team contributes to articles in high-impact journals, with the IMAGE-team itself leading articles in journals like Nature Climate Change, Nature Sustainability and Nature Communications on climate policy, climate impacts on energy, bioenergy, and nexus-focused scenarios. Moreover, 11 PhD theses have been written by team members since 2015 - also contributing to the role of the IMAGE project for researchers to advance their careers.

Figure 2.2
Number of papers per year published by the IMAGE team based on Scopus. The figure counts all papers published by core-IMAGE-team members and other explicit IMAGE applications

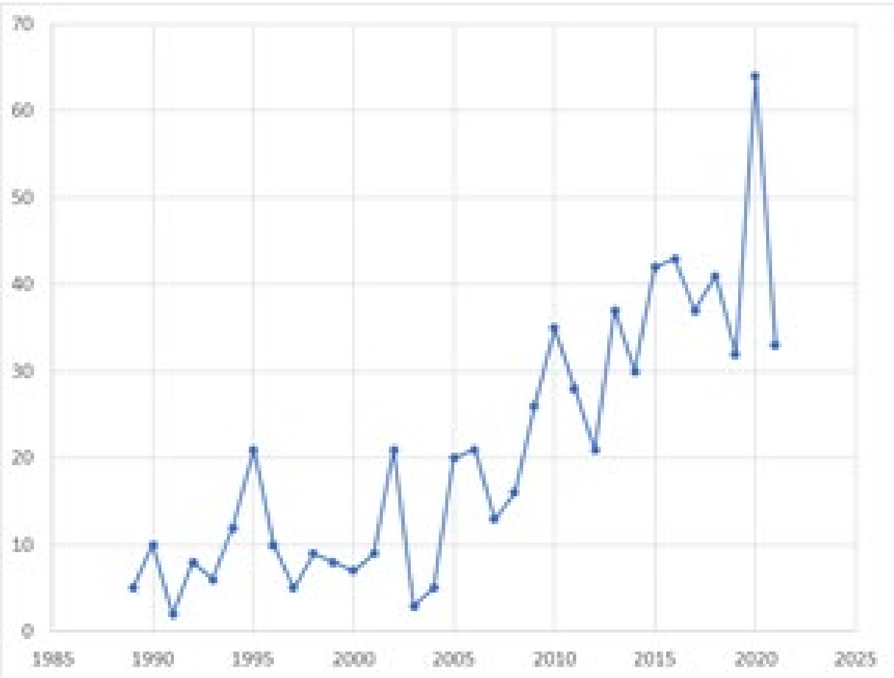


Table 2.3
PhD thesis published by IMAGE-team members in the period 2015-2021

IMAGE researcher, year	PhD thesis
Clifford Chuwah, 2015	Possibilities for integrated policy for air quality and climate change
Vassilis Daioglou, 2016	The role of biomass in climate change mitigation
Barbara Koelbl, 2016	Deployment potential and macro-economic impacts of carbon dioxide capture and storage in the future energy system

IMAGE researcher, year	PhD thesis
Mariesse van Sluisveld, 2017	2°C through different lenses: Evaluating long-term energy system change for a 2°C-constrained world
Angelica Mendoza Beltram, 2018	Deepening the uncertainty dimension of environmental Life Cycle Assessment: addressing choice, future and interpretation uncertainties
Oreane Edelenbosch, 2018	Energy demand futures by global models Projections of a complex system
David Bijl, 2018	Sustainable resource use in the global water-food-energy nexus
David Gernaat, 2019	The role of renewable energy in long-term energy and climate scenarios
Mathijs Harmsen, 2019	Non-CO2 Greenhouse Gas Mitigation in the 21st century
Anteneh Dagnachew, 2021	The power of energy. Synergies and trade-offs of achieving SDG7 targets in Sub-Saharan Africa – A model-based analysis
Sebastiaan Deetman, 2021	Material use in the 21st century

2.3.3 Model development

In 2014, the IMAGE-3 model was finalised. In 2020, we completed the IMAGE 3.2 model. The IMAGE 3.2 model goes beyond the earlier model versions in several ways, as indicated in Table 2.4.

Table 2.4
Key model improvements in the IMAGE 3.2 framework

Model component	Improvement
General	The model has been fully calibrated up to 2015, and where possible, even to a more recent date (2018 for energy system variables, 2020 for renewables capacity and CO_2 emission data). Moreover, the base year for scenario analysis was set at 2020, implying that scenarios follow the same trajectory in the 2015-2020 period
Energy demand	The model now has a detailed representation of energy demand in transport, industry, buildings, services and agriculture. For transport, the model now describes all relevant transport modes and technologies within these modes based on recent data and innovations (particularly for electric vehicles). Also, the technology costs of electric and hydrogen-fuelled transport technologies were updated. Moreover, an explicit representation of energy use of gas pipelines was added and calibrated to IEA data. Finally, also a new CNG fuelled car type was added. The model describes steel production, pulp and paper, chemicals and feedstock, cement and food products for industry. All sectors contain disaggregated technology descriptions. Ammonia demand (as part of chemicals) has been linked to agricultural production. The buildings sector represents energy services in the residential sector - including a detailed representation of insulation. The service model describes energy use for heating, cooling, lighting, appliances, and other services in the service sector.

Model component	Improvement
	For buildings, also an explicit representation of insulation levels and renovations for the housing stock was added. In addition, heat pumps were added as an additional heating technology. The agriculture sector, finally, describes energy use for irrigation and other functions.
Energy conversion	In energy conversion, details were added to electricity representation and hydrogen production (using a residual load duration curve approach). The data on existing plants was updated. In addition, hydropower modelling was made dynamic (instead of a prescribed fraction of total potential) using the information on potential and cost via cost curves. Also, an improved technological learning formulation was introduced. Finally, rooftop PV was added as an additional form of PV power supply.
Energy supply	Bioenergy modelling was greatly improved, using dynamic land-use change emission factors based on the IMAGE-land model and adding biofuel production with carbon capture and storage technology routes. Moreover, a BECCS option was added to liquid biofuel production. The data on fossil fuel reserves and resources was updated. Climate impacts on different forms of renewable energy (solar, wind, hydropower and bioenergy) were added to the model.
Land use	In land use, the number of crop categories was increased to 16 representing all crop production reported by the FAO: wheat, rice, maise, tropical cereals, other temperate cereals, pulses, soybeans, temperate oil crops, tropical oil crops, temperate roots & tubers, tropical roots & tubers, sugar crops, oil palm, vegetables & fruits, other non-food, luxury crops, spices, plant-based fibres). Deforestation due to other reasons than agricultural expansion was improved based on FAO data in combination with satellite data from ESA-CCI. Anthropogenic land use for other reasons than agriculture or built-up is accounted for.
Food demand and production	The link between the agriculture-economic model MAGNET and the IMAGE model was significantly improved concerning climate change effects and exogenous and endogenous trends in crop yield changes
Land-based mitigation	The modelling of land-based mitigation in IMAGE and MAGNET was improved, including avoided deforestation and afforestation through MAC curves in FAIR and accounting for the interaction non-CO_2 mitigation and the agriculture and food system. Greenhouse gas emissions from peat land degradation were included
Water	The water modelling in IMAGE linked to LPJmL was improved, introducing municipal, energy and industry water demand in LPJmL and making it possible to account for environmental flow requirements. The external module GLOFRIS modelling river flood risk was improved and modelling of coastal flood risk.Finally, also the external water quality module modelling nutrient emissions to surface waters and ground water has been improved, especially the modelling of nutrient emissions from households in cities and rural areas.

Model component	Improvement
Non-CO_2	All non-CO_2 GHG marginal abatement cost curves were updated based on recent literature.

2.3.4 Progress in light of the advice of the Advisory Board

Table 2.5 summarises the advice of the 2014 Advisory Board and how it was handled by the IMAGE -team. The advice of the 2018 Advisory Board (that looked at specific questions) is summarised in Table 2.6 and the progress made by the IMAGE team.

Table 2.5
Advice of the 2018 Advisory Board and the way the IMAGE-team implemented it

	Advisory board	Response
Transparency	Extent website/wiki to include more details on data and equations	New website launched in 2020. Data shared via online USS, IAMC database New information added to wiki
	Strategy for open data and open model access	Data is open access. We are working open model access
	More use of Advisory Boards	We implemented new advisory board system and organised meetings in 2018, 2020
General methods	Quality assurance plan	Quality assurance plan was made
	Focus on missing links between issues	We added several new feedbacks (e.g. nitrogen; climate on renewables)
	Replication of issues – why?	We considered reasons for 2 hydrological models; are working on agri-economic model strategy
	Rethink regions	We did not change regions as announced
Evaluation and uncertainty	Perform evaluation / uncertainty analysis – not only at component level	Considerable uncertainty analysis was done; also via scenarios - but mostly at level of submodels
Staffing	Permanent understaffing is a problem; also restore balance between permanent / temporary staff	Staffing is less of a problem than in 2014 - although it still plays a role.
	Continue on pathway of cooperation with other institutes	We are really happy on our collaborations
Future strategy	Identify user groups and explore their interests Focus on nexus/SDGs; prioterise development	We have in some projects worked with other user groups (e.g. non-state actor project). Still main users are policymakers and science Nexus and SDGs become more

	Advisory board	Response
		important (e.g. PICASSO and SIM4NEXUS project)
	Formulate strategy for ownership and quality control	Quality control standard was made
	Think of how to include extreme events	We have not included extreme events in the model
	Update base year	The base year was updated to 2015
	Include existing policies in a realistic way	We have significantly improved policy representation
	Health and water are important issues	We are working more on water; we do have a health model and are going to invest in it.

Table 2.6
Advice of the 2018 Advisory Board and the way the IMAGE-team implemented **it**

Advisory board	Response
Progress to date: Impressive	Thank you
Further model development: focus areas nexus and circular economy	This advice is consistent with some of the focus activities in Hor-2020 projects and e IMAGE research activity. Moreover, it was also taken up in the Strategy 2022-2027
Reimplementation SSPs: good idea	We have indeed reimplemented the SSPs, following the advice of the 2018AB
Dealing with heterogeneity fits IMAGE strengths	We have income groups and distinctions urban/rural in the residential model and partly in the representation of food demand. We are looking into the characterisation of lifestyle. We also tried to add heterogeneity in transport but failed to get sufficient data.
Ideas for reaching out to non-governmental actors	Limited action so far. We do work with some foundations and as part of the Bend the Trend activity with WWF.

Based on the overview provided in Section 2.3.3 and Section 2.3.4, we conclude that regarding the priorities set for the model development in the 2015-2020 period and the specific recommendation of the Advisory Boards, we conclude that these have helped to guide development activities. Most efforts were paid on improving the IMAGE model further in terms of representing response strategies (e.g., land-based mitigation, the better representation of food demand, and mitigation strategies in energy demand and supply). Attention was also paid to better integration, e.g., the focus on bioenergy (in terms of land, climate, energy and biodiversity consequences) and land-based mitigation. Model development also focused on further model improvement in terms of impact on human development concerning access to energy and food and climate impacts on agriculture and energy systems. Finally, uncertainty aspects have been taken up at the level of individual model components (see individual publications).

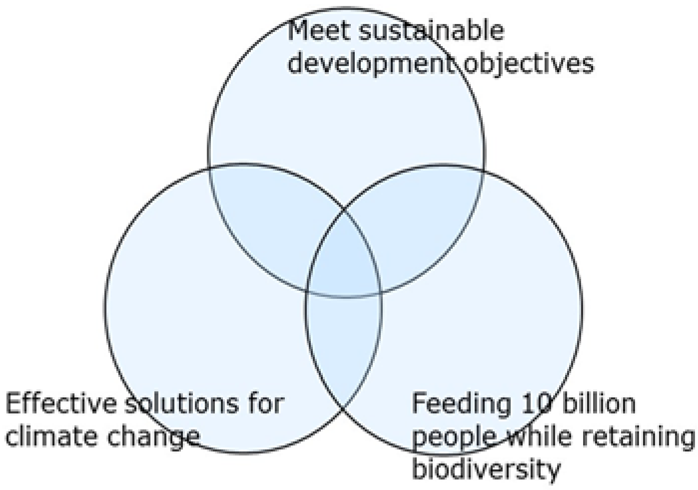
3 Key questions and priorities for IMAGE development

3.1 Key model characteristics and focal questions

The IMAGE model development and application has been quite successful in the past period. The strategy for the 2022-2027 period will build upon the progress made and add several new elements. The current strengths of the current IMAGE system as identified in Chapter 2 are:

- The detailed, biophysical representation of human activities - allowing a direct assessment of implications for global environmental change and human development.
- The simulation environment - allowing to explore non-optimal pathways and dynamic interactions.
- The linkages between the energy and land system - representing key drivers of global environmental change.
- The detailed geographical detail, using a 5x5 minute grid and 26 socio-economic regions.
- The focus is on response strategies (rather than baseline development).
- The focus is on system linkages and integration.

Figure 3.1
Three focal questions for IMAGE application and development



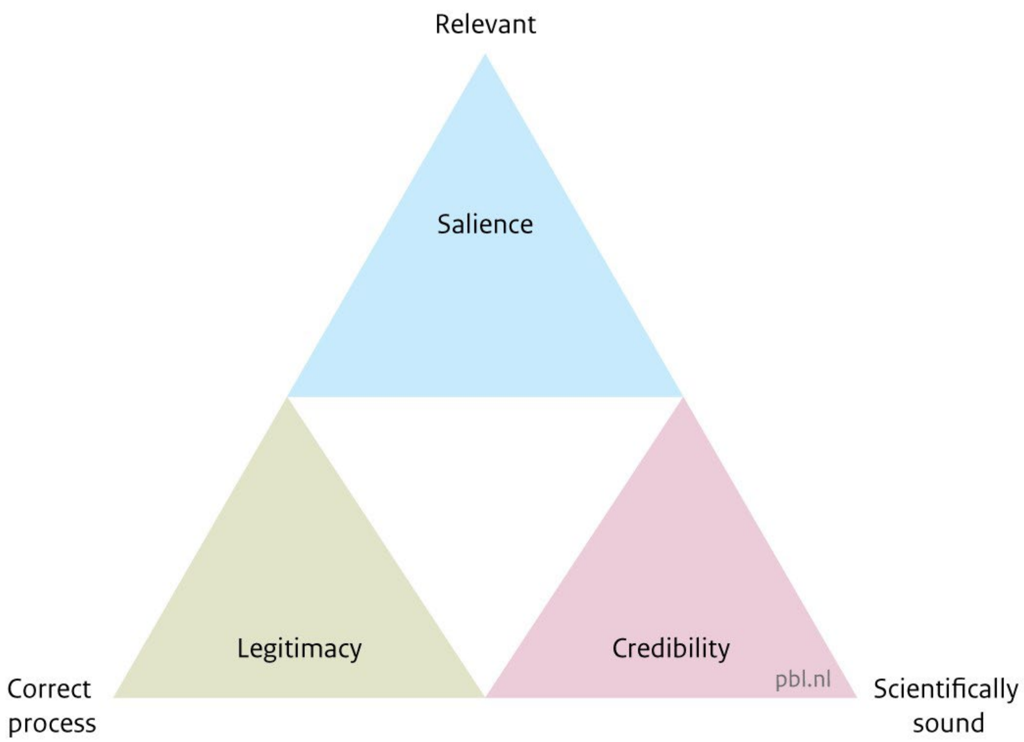
In general, we believe that the key focal questions identified for the 2015-2020 period are still relevant for the 2022-2027 period. Therefore, these three questions continue to guide the research (as also indicated in Figure 3.1).

- ***What are effective response strategies to deal with climate change?***

- ***What strategies could provide sufficient food for 9 billion people by 2050 while conserving biodiversity and providing ecosystem goods and services?***
- ***What strategies could implement multiple sustainable development objectives (SDGs/Planetary Boundaries) simultaneously?***

The Global Environmental Assessment (GEA) project formulated three criteria for successful linking research, assessment, and decision-making [15]. This means that work should be salient, legitimate, and credible. A key feature of integrated assessment work is that it should be policy-relevant or salient. The GEA defined it as relevant information for an actor's decision choices or the choices that affect a given stakeholder. In the context of IMAGE, this includes policymakers and society at large (see further). It also means that the work should be timely and, to some degree, new. Legitimacy refers to whether an actor perceives the process in a system as unbiased and meeting standards of political and procedural fairness. Legitimacy is increasingly emphasised as a criterion and encompasses transparency in the process and, where relevant, participation. The criterion credibility refers to whether users perceive information as meeting standards of scientific plausibility and technical adequacy. This is important, as, In the policy dialogue, information needs to be authoritative, believable, and trusted to be useful. This often implies using scientific methods, including the use of state-of-the-art methods and publication in peer-reviewed journals.

Figure 3.2
Salience, Legitimacy and Credibility as criteria for successful integrated assessment work



We have used these criteria to group priority areas for the IMAGE strategy in the 2022-2027 period. The selection was done in multiple sessions of the IMAGE team, using the advice of the

IMAGE Advisory Board and building upon the strategies for the international work at PBL and the team Climate, Air and Energy.

Salience

To be relevant as an integrated assessment model in the field of global environmental change, we believe the model needs to be improved regarding the following four themes (that emerged from the process of elaboration with the team, Advisory Board, the IMAGE steering group and the comparison with IMAGE strengths and weaknesses):
1.1 Identifying strategies to reach sustainable development goals
1.2 Identifying strategies to reach net-zero emission systems
1.3 Representing circular economy and material flows
1.4 Reconciling multiple claims on land

Legitimacy

For the legitimacy of the IMAGE work in the next few years, the work needs to be based on an open science strategy.
2.1 Developing and implementing the IMAGE open science strategy
2.2 Better representation of response strategies and policies

Credibility

Several elements are important regarding the credibility of the IMAGE work.
3.1 Developing more efficient methods for model use
3.2 Model language
3.3 Other methodological improvements in IMAGE-energy
3.4 Other methodological improvements in IMAGE-land
3.5 Other methodological improvements in IMAGE-integration

It should be noted that there is some overlap in these three categories. For instance, the issues listed under salience also requires an implementation based on legitimacy and credibility (in the Appendix, we list some of the interactions). We only use them here to categorize the ambitions we have formulated. We further elaborate on the priority areas in Chapter 4. In order to elaborate the elements of salience and legitimacy further, we need to define the funders and users of IMAGE work for the 2022-2027 period.

3.2 Funders and users

Most of the funding for IMAGE activities comes from:

- institutions funding applied research (DG Research, NWO, foundations),
- government agencies and some other clients with specific questions (DG Climate, DGIS, I&W, EZK but also WWF, UN Environment), and
- PBL Netherlands Environmental Assessment Agency (PBL funded projects),
- international assessments (funded via Netherlands' ministries).

These groups are also expected to remain the main funders in the future. Consistent with the advice of the Advisory Board, we will look for other funders, including foundations and NGOs.

In terms of users, this is slightly different from funders. Critical users include policymakers, Scientists, Assessments, Education, Societal organisations and Public at large. So far, IMAGE has mostly been used for the first four categories. Policymakers have used the information to explore the consequences of decisions related to climate, land use, and other environmental issues. IMAGE (and other IAMs) also plays a critical role in providing scenario information for other research communities and scientific assessments. Finally, IMAGE information also plays a role in education (for instance, the IMAGE User Support System (CD-ROM and online) has been extensively used by universities worldwide). We do see these user groups as also important in the future. Although defined as secondary users, we intend to reach out more to other societal organisations (businesses, NGOs) and the public at large. For the users of IMAGE work, information can be relevant both directly (i.e., in direct contact) or indirectly (e.g. via published papers that influence decision-makers or the public in general). For models such as IMAGE, the indirect information flow is at least as important as the direct one – and we will continue to prioritise this important output channel.

In addition, contact with potential users of IMAGE information will be intensified by way of the following two activities: a) We intend to make more use of the IMAGE Advisory Board to check whether we are working in the right direction in terms of model application and development. Following the advice of the Advisory Board, we will ensure that users are sufficiently represented on the Board. b) We plan to discuss the details of the direction of model development and application with several clients, as indicated in this document. Working for new users could mean that the role of various societal groups in our assessments will need to be addressed more specifically. This can be done, for example, by cleverly designed model application, such as the sectoral approach currently used in work for the Convention on Biological Diversity. In other cases, it will require model adoption – this is consistent with our strategy to consider how the heterogeneity of various societal groups could be addressed in the model. For instance, adding distinction between rural and urban populations allows better identification of the role of cities in addressing global environmental change issues.

4 Critical focus areas for analysis and model development

4.1 Priority areas related to policy relevance (salience)

Four areas were selected as focus areas for model development in the context of policy relevance: 1) SDGs, 2) net-zero, 3) circular economy/materials flows and 4) competing claims on land.

4.1.1 Identifying strategies to reach sustainable development goals

Challenge

Current development trends are far from sustainable: there are serious signs of environmental degradation. Around 2 billion people lack access to modern energy services, and almost 1 billion people suffer from hunger. In 2015, the world agreed upon the Sustainable Development Goals to work towards a development strategy that would 1) ensure environmental protection, 2) eradicate poverty and 3) allow for meaningful lives. While scenarios have allowed policymakers to identify strategies for reaching environmental goals (such as for climate), such scenarios are still lacking for achieving sustainable development goals simultaneously. Still, there is a strong need for such scenarios - also to identify possible synergies and trade-offs. It should be noted that the broader, sustainable development view is also critical for more specific issues like climate policy. Without considering the impact on other sustainable development issues, there could be serious trade-offs reducing societal support.

Contribution IMAGE

The detailed representation of the IMAGE system and the focus on many critical development topics imply that IMAGE has been proven useful for sustainable development scenarios. The model also already describes processes for many SDGs. In particular, the simulation environment of IMAGE can be very useful to describe possible trade-offs and synergies (as these issues are sometimes toc complex to do meaningful optimisation).

Implications for model development

- *Identifying and implementing critical indicators*. The paper by van Vuuren et al., 2021 suggests a set of around 40 indicators that represent the 17 SDGs reasonably well. As a first step as part of the IMAGE work on SDGs, we will identify which of the 40 indicators are already represented and which can be represented based on model development. Some indicators might not be relevant to include (such as those related to policy infrastructure and conflict).
- *Adding a simple economic model*. We will add a simple economic model to the IMAGE framework (based on the simple economic growth model already used for cost-benefit

analysis) to describe income distribution, investment needs associated with the SDGs, and possible consequences of different strategies for economic growth. The income distribution outcomes can be coupled to the current representation of income quintiles and, therefore, the formulations of access to food, energy, and water.

- *Heterogeneity.* We will better represent issues related to heterogeneity. The critical point is that of inequality and access to resources. We will look further into a better representation of these issues, also concerning environmental change. A second topic in the area is the representation of the differences between the urban and rural population.
- *Adding GISMO/FASST.* We will work towards linking or hard-coupling relevant models to the IMAGE core model to represent SDG-related issues better. This includes the GISMO model (representing health and demographics) and FASST (air pollution).
- *Scenario development:* We will develop several scenarios that explore how to meet the SDGs showing possible synergies and trade-offs. Such scenarios can be based on strategies such as 1) changing lifestyle and consumption, 2) technology-focus and 3) redistribution.

Implementation

Implementation could, first of all, take place in externally funded projects (e.g., the PICASSO project running from 2021 to 2025). Still, some critical connections can be made with the core development programme (e.g., communicating new indicators via USS and model coupling). The aim is to show progress in this area by several publications that show synergies and trade-offs between SDGs and specific strategies that can avoid the latter.

4.1.2 Identifying strategies to reach net-zero emission systems

Challenge

In the 2015 Paris Climate Agreement, Parties agreed to keep the increase in global average temperature to well below 2 °C above pre-industrial levels and pursue efforts to limit temperature rise further to 1.5 °C (Article 2). To reach these objectives, Parties further agreed to "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century." (Article 4). This balance between greenhouse gas (GHG) emission sources and sinks can be defined as GHG emissions neutrality. The concept of emissions neutrality has gained interest among policymakers.
Many governments have formulated net-zero emission targets, e.g., EU, China, Japan and South Africa. There are critical questions regarding the timing of sectoral and regional net-zero targets, the link with overall climate goals and methodological choices (e.g., the choice of GHG-equivalence metric) and links to policy-text. In addition, the question is how net-zero can be reached in time. It will also be important to link climate action to other SDGs: What is the impact on the SDGs, and conversely, what is the effect of achieving SDG targets on net-zero? This can nicely link to the topic of SDG representation in IMAGE.

Contribution IMAGE

IMAGE has a detailed representation of sectors relevant for climate change mitigation, including the energy and land-use system. The physical representation allows for evaluating the consequences of net-zero emission strategies and the relative sectoral contributions. Still, not all options are (well) represented – which does limit the overall mitigation potential. The challenge is to explore different mitigation strategies across the different sectors while keeping up to date with the latest developments and showing the different strategies' consequences. Additionally, the model framework needs to enable analyses of a wide range of policies and targets leading up to mid-century net-zero targets. Additionally, we need to enhance our ability to generate scenarios that are 'fit for use'. That means both improving the tool set that allows us to generate a wide variety of scenarios (referred to under scenario building) and connecting short term policies and goals (NDCS and related targets and policies) with net-zero targets. At the end of the period that this strategy document spans, we are probably looking at intermediate targets to reach net-zero around 2040ish. We need to make sure we are ready for such analyses.

Implications for model development

- *Sectors.* To assess net-zero targets set by governments and non-state actors, it is essential to analyse how to reach such targets. As such, we need to keep the IMAGE model framework state-of-the-art by focussing on improving the representation of mitigation potential and considering advanced mitigation options, particularly in the **hard-to-abate sectors**. Such an improvement can be aided by an uncertainty analysis of key and uncertain mitigation options (e.g., non-CO_2 or land-use CO_2). The 2021 “Hard-to-abate study” by the IMAGE team can help to identify focus areas. This also includes improving sectoral interlinkages, including the connection between energy and land, which is key to enable integrated system analysis. For example, steel and cement production is not coupled to sectors demanding those products.
- *Policy.* A wide range of net-zero targets is discussed by policymakers, for instance, domestic targets at the country level or for specific actors and sectors. Not all policies can be adequately represented at the moment. This involves action by non-state actors. IMAGE could also be relevant for land-use-related policies, although one issue is dealing with different accounting mechanisms.
- *Feasibility.* At the moment, IMAGE mostly focuses on geophysical, technical, economic and environmental feasibility concerns of net-zero targets. Societal factors are mostly not considered. We intend to improve this via cooperation (see 4.2.2).
- *CDR.* Both scientific and societal critiques of carbon capture, usage and storage (CC(U)S) necessitate the study of alternatives. It is important also to add alternative or underexposed aspects of carbon capture that need further development, such as the capacity of soil carbon, direct air capture (DAC) and improvement of CCS technologies over sectors. In this context, it is also our ambition to better represent AFOLU measures and to explore the complementarity of -or potential discrepancies between- national and global goals and the role of the AFOLU in the international transfer of mitigation outcomes.
- *Scenario building:* With the advent of the NDCs and net-zero targets, the integrated assessment community requires different scenarios. Creating some of these scenarios with IMAGE is cumbersome (dependent on timing and peaking profiles). A flexible route to develop scenarios that satisfy particular constraints and possibly multiple targets requires adapting the IMAGE policy (FAIR) and scenario optimisation (FAIR-SiMCaP) models. Secondly, we want to be able to analyse multiple pathways that achieve the same target. The other side of the same coin is getting a better grip on the

costs of technologies and policy measures. Non-cost-optimal scenario analysis can reveal what it means to reduce dependence on specific technologies.

Implementation

Focus on climate mitigation strategies is at the core of IMAGE work at PBL. Therefore, the activities above are critical to be funded via the overall work programme – although we also expect external funding via DG Climate Action and DG Research and Innovation of the European Commission. Among the highest priorities of the elements listed here are the importance to keep the mitigation options up to date and improving the scenario building activities.

4.1.3 Representing circular economy and material flows

Challenge

There is an increasing interest in the consequences of the high material throughputs of the current economy. This is based on possible resource scarcity and the implications for energy demand and, hence, GHG emissions. While climate policy analysis now often looks at efficient steelmaking or alternative steelmaking technologies with less GHG emissions, it hardly looks at the question of whether steel demand can be reduced. There is an urgent need for looking at options to reduce resource consumption - in direct relation to global environmental problems.

Contribution IMAGE

Compared to other IAMs, IMAGE has a relatively detailed representation of the physical world in terms of sectors, technologies, resource availability, land use, and energy use. In the last years, the model has also expanded in its representation of the material world through different activities with more details in 1) the production of specific materials, 2) demands for materials, and 3) material stocks in different sectors. Connecting these different parts of the model would allow representing the physical flows of materials and accumulated stocks throughout the entire system and, importantly, assessing the full energy and material metabolism. Central material and energy interactions across sectors (e.g., transport use impacting demand for steel and cement) could, as a result, be assessed (in a similar way to the water, energy, and land nexus) and could potentially impact baseline development pathways. The materials-energy connection would also allow combining analysis of climate change mitigation and biodiversity policies with circular economy measures. Moreover, broader implications of transition pathways resulting from climate policy, lifestyle change can be evaluated, and impact indicators expanded towards resource use, economic effects, and wellbeing.

Implications for model development

- *Taking stock of the current situation.* The first step would be to assess information on current material flows and resource use throughout the system and compare these to the representation in IMAGE. Through Sankey diagram analysis, an overview of resource flows can be visualised under different scenario assumptions (this will be done in cooperation with Freiburg University and the CE team at PBL).

- *Model development*. Several model development activities are ongoing and will be further developed within the current framework.
    - *Demand and materials flows.* Move from energy service to end service and connect to wellbeing (so instead of focusing on transport energy use, the focus shifts towards mobility but especially the underlying reason for mobility). Moreover, include a representation of materials stocks in products/structures/end services (e.g., buildings) and formulate inflows (production) and outflows of these stocks.
    - *Expand coverage*. Several critical materials are not included in IMAGE. Therefore, the ambition would be to expand the coverage of associated materials used for products/structures/end services. Moreover, the CE perspective also requires the representation of the recycling and mining industry as well as a representation of the trade of materials.
    - Representation of circular economy measures such as product sharing systems and other circular business models, material substitution, an extension of product lifetimes, design for reuse, repair and recycling.
- Completing model development would significantly improve the IMAGE model with new definitions of end-use, intermediate sectors, and modules with dynamic input and output matrices, allowing for dynamic lifecycle type analysis.
- *Link with ongoing work at PBL.* PBL is building an economic model looking at the circular economy. We will ensure that information is exchanged between these two systems. Furthermore, the GLOBIO GRIP database may be used to assess material demand related to road infrastructure developments.
- *Model application.* Designing scenarios of lifestyle change (incl. circular use and circular design), household choices, policy measures to assess resource use, welfare implications and economic impacts.

Implementation

Implementation is already partly happening as part of the collaboration with the UU and CML (e.g. as part of the PICASSO project and in activities related to the International Resource Panel). Moreover, cooperation is also possible with the CE team within PBL. We expect some of the activities above to be dependent on external funding. In other words, most of the activities described above will be part of the work programme in the coming years, but the depth depends on further funding.

4.1.4 Reconciling multiple land claims

Challenge

Land plays an important role in global environmental change and is key to achieving many of the SDGs. As such, it is relevant to all three focus questions for IMAGE (Section 3.1): climate change mitigation, biodiversity & food, and other SDGs. Meeting these goals will put claims on future land use, and pathways towards sustainable land and food systems will have to account for various goals. Society has to find strategies how to combine these claims and avoid critical trade-offs. At the most aggregated level, the key aim is to explore how food security can be achieved while preserving biodiversity and contributing to climate policy. From this, several other objectives can be derived.

- To identify possible pathways towards sustainable land & food systems under climate change.
- To better quantify and map the contribution of the agricultural and forestry sector to climate change mitigation.
- To understand how water policies at different levels influence future water demand and supply.
- To examine the role of the AFOLU sector as source/sink related to net-zero emission targets and other land claims.

Contribution IMAGE

A key feature of IMAGE is its spatially explicit representation of land use and land-use change-related variables. Its grid-based representation of land use in IMAGE-land at 5x5 minute resolution is a relatively high-resolution approach with a unique IMAGE feature compared to other IAMs. Recent cooperation between IMAGE and GLOBIO has proven fruitful in producing biodiversity centred scenarios, with various high-level products (Rio scenarios, Bending the Curve, Post-2020), and great visibility in multiple assessments (e.g. UNEP, IPBES, WWF). Furthermore, the close cooperation with the MAGNET team has proven very successful over the years, developing successful exploratory scenarios (SSPs) and policy scenarios focusing on climate change mitigation, biodiversity, and dietary change.

Implications for model development

Considering the complex challenges stated in the first part of this section, and taking into account the specific strengths of IMAGE, we identified the following four focus areas:

- *Grid-level detail for land use and more detailed representation of land management.* In IMAGE, agricultural land use is represented in a relatively homogeneous way within regions (yields varying in response to soil and climate only). However, locally different management systems, levels of input, and policies greatly impact agriculture's efficiency and environmental impact between locations. Moreover, many policies proposed to reduce the environmental impacts of agriculture depend on management rather than absolute changes in an agricultural area (e.g., more trees in farmland/agroforestry, organic farming, alley cropping, higher soil carbon levels through reduced tillage or different residue management). Including these options and their impacts on GHG emissions, nutrient cycles, and biodiversity is key to answering the questions IMAGE wants to address in the coming years. To address these topics, we plan to revisit the land use representation in IMAGE-land to include heterogeneity in management systems and intensity levels. In addition, we will explore whether an intermediate layer between the regional and the grid level can be added, for example, at the national or sub-national level to improve land use allocation. Lastly, crop management representation in the coupled LPJmL should also be improved based on management information in IMAGE-land, for example, with dynamic management factors in LPJmL, residue management, and irrigation systems.
- *Options and pathways to sustainable land and food systems and their interactions*. Expected growing population numbers will require higher agricultural yields, which can be achieved by agricultural expansion and intensification. These developments are region and crop dependent and are further modulated by trade and regionally differing

outcomes of climate change. At the same time, future dynamics will be influenced by other demands for land (for timber, settlements, biodiversity, Ecosystem Services, bio-energy production, carbon sequestration) and the need to curb agricultural GHG emissions. IMAGE allows for exploring pathways towards sustainable land and food systems, including options like plant-based diets (incl. exploring the potential and consequences of artificial meat), food waste reduction, and improved water and nutrient efficient agriculture. So far, these questions have mainly been addressed in the MAGNET model, which is used in successful cooperation between the PBL and WEcR teams which we aim to continue. As the link between MAGNET and IMAGE is only partial and as we cannot run the model in house, we in parallel want to explore an alternative tool (see also section 4.3.3). Based on an internal discussion and availability of tools, we decided to get started with the simpler agroeconomic partial equilibrium model SIMPLE-G, which might be fully integrated into the IMAGE framework in the longer term. In 2022, we will get acquainted with SIMPLE-G (course) and start applying it in a scenario study, possibly parallel to MAGNET. In general, the land demand from other non-agricultural sectors and demands (like timber, urban area, nature conservation), and their interaction with water, need to be integrated with the land model. Specifically for forestry, an inventory of the current situation has been prepared, and in 2023 together with NLG, modelling capacity MAGNET and TIMER (see also below), ambition level, and next steps for modelling the forest sector (supply and demand) have to be decided.

- *Biodiversity scenarios, in cooperation with GLOBIO.* The collaboration with GLOBIO will be continued in several upcoming activities for IPBES and Bending the Curve follow up. The ambition is to maintain and strengthen this position, ensuring the high quality and relevance of this work. Model development will focus on a more detailed representation of land management (issue 1) in IMAGE and GLOBIO. More specifically, this will include simplified calculations of MSA and other biodiversity indicators (e.g. BII) as standard calculations in IMAGE-land to enable biodiversity target seeking scenarios.
- *Further integration to represent multiple claims on land (including mitigation) and nexus issues.* IMAGE has a detailed representation of most sectors impacting the environment. However, for practical and historical reasons, the models representing the land and water sectors, energy and nutrient sectors are not hard-coupled. Improving this would allow for a better understanding of the linkages between the human use of resources (e.g. wood in buildings) and the land use that provides the resource and its related impacts. Specific improved links are the following:
    - Coupling (hard-coupled or automated interaction) of the land and energy system to make the dynamic exchange of emission and climate change impacts possible. This also allows for improved assessment of adaptation measures.
    - Coupling of timber demand to end services such as paper, buildings, furniture and bio-energy to improve assessment of the circular economy on wood.
    - Include simplified use of nutrients (based on the GNM model) and pesticides to consider impacts of land use/management changes.

- Coupling of water modelling in LPJmL with TIMER to consider the effect of limited water availability on water demand for industry, energy and households.

Implementation

The issue related to multiple claims on land is important for SDGs (hunger), biodiversity and mitigation. Therefore, improving our model capacity here is important. At the same time, how much we can fulfil the ambition laid out above depends on the capacity (including, for instance, external funding). We will, on an annual basis, prioritize specific actions. Among the highest priorities are the representation of the agriculture economy and the continued integration of different IMAGE elements.

4.2 Legitimacy

Several activities are critical for legitimacy in the future. One notion is that increasingly science is questioned. Regular contact and an open science approach might be important responses to this trend. This means that it is important to establish regular contact with stakeholders and the things elaborated below. Also, regular contracts with the advisory board are important to ensure legitimacy.

4.2.1 Developing and implementing the IMAGE open science strategy

Challenge and IMAGE contribution

Open source and open data coincide with long-standing scientific traditions of transparency and reproducibility. The IMAGE team recognises these values and, at the same time, sees that funding and publication regulations move in the same direction. Other IAM teams are already open-source (GCAM, REMIND-MAgPIE) or moving towards it, thus adding competitive pressure to do likewise. Furthermore, an open-source model framework and open data access can foster cooperation with a range of partners within projects, inspire new avenues of research. Finally, it can strengthen and broaden support for integrated assessment research with IMAGE. However, moving to open source is not an easy step. It requires considerable time investments.

Implications for model use and development

- Below we indicate our ambition. However, the implementation does depend on capacity. We believe that it will be necessary to dedicate time to this topic for fully implementing ambition explicitly. As open science is also an important topic for PBL as a whole, we are planning to discuss within the IMAGE team and with PBL management how sufficient capacity can be allocated to this issue.
- *Open source in 2027.* The ambition for 2027 is to be fully open source by having its entire model code on Github, including the input and output data. This requires not only a gradual process, but also an investment in code quality.

- *Model documentation.* We will continue to ensure that the model is well documented. We will work towards more automatic documentation implemented as part of the Python programming code.
- *Communication*. The main channel is the IMAGE website (www.pbl.nl/image), the IMAGE model documentation (models.pbl.nl/image), in combination with the @IMAGE_PBL twitter-account.
- *Data sharing.* We will share the latest scenario data via the IAMC database and upload the data to the IMAGE website (using the IAMC reporting template or other formats). Published datasets will be provided, including metadata, enhancing the relevancy of the data. The ambition is for each IMAGE publication to coincide with a short website article, data sharing, code sharing, and social media communication.
- *Data visualization*. We will develop an online visualization tool to explore model and scenario (meta)data.

4.2.2 Better representation of response strategies and policies

Challenge and role of IMAGE

The number of climate policies has increased steadily in the past decade, especially since the adoption of the Paris Agreement in 2015. IMAGE has played an important role in analysing these policies and their expected effect on greenhouse gas emissions until 2030. It is the model with the highest coverage of detailed policy measures of all IAMs. Its 'current policies' scenario has been used in annual reports for DG CLIMA of the European Commission, in the annual UNEP emissions gap reports, and in various Horizon 2020 projects (notably CD-LINKS and ENGAGE). The team has played a pivotal role in developing the model protocol for current policies scenarios used by other IAMs. The better representation of policies could also be listed under salience; we want to highlight the need to correctly represent the policies discussed by policymakers.

Implications for model use and development

Given the fast developments in international and national climate policies worldwide, IMAGE will need to continuously work on its coverage of targets, measures, and instruments to stay relevant. Moreover, it will need to regularly provide scenarios that reflect the latest status of policy implementation. Focusing on the feasibility of the scenarios will further be an important next step. Therefore, the following four focus areas for model development and application can be identified:

- *Representation of leverage points in all parts of the model.* Model development will need to continue in all parts, with special attention to the industry, buildings, and land-use sectors, where the representation of policy measures is currently lower than in electricity and transport. Further model improvements will be needed, particularly on representing specific mitigation policies, such as taxation, renewable and energy efficiency standards. Next to improvements in individual sectors, special attention needs to be given to the interactions between policies in different sectors and more overarching policy frameworks such as climate laws, as policy packages will become increasingly important. Input from stakeholders will be crucial to represent the key policies (a process started in the CD-LINKS project with the expert review of the current policies scenario protocol).

- *Multiple scale representation.* New model developments are needed to model the mitigation impact of policies by non-state (need to have) and subnational (nice to have) actors and quantify the degree of overlap between actors' impacts and the impact of national policies. The sub-national level is particularly important for Australia, Canada, and the USA. Representing the perspective of these different actors would increase legitimacy.
- *Representation of feasibility concerns* (need to have). Several projects and organisations, such as IPCC and the ENGAGE and other projects, are developing methods to represent the notion of feasibility beyond the technical, economic and biophysical representation included in the models. These other aspects (such as societal aspects) can be assessed expost but might also be fed back into scenario development. Such linkages with and insights from social sciences will become increasingly important in answering questions of 'how do we get there'. Boundaries or thresholds will need to be defined in consultation with stakeholders to reflect' real' feasibility concerns, an important pillar of legitimacy.
- *Standardisation*. We have already started a standardisation process with the modelling protocol and documentation, which can be further refined and, to some extent, automated. This includes automatically reading the protocol sheet with numerical policy targets into the IMAGE/TIMER settings files (nice to have). It is important to annually update the current policies scenarios based on new policy developments and ensure that more people can do this work. The current R and Excel-based tools to check whether all policy targets as specified in the protocol are met would be translated into Python (need to have), thereby automating the process further. Another, more technical, improvement would be to extend policies and targets beyond their target year by measure, based on knowledge of policy proposals, rather than for overall GHG emissions of the scenario, based on generic assumptions such as 'similar effort' (nice to have; see also 4.3.1 on more efficient methods).

Implementation

Effective representation of policies in IMAGE is at the core of the IMAGE work. We will ensure that the representation of leverage points is covered in all projects and the work programme. The same holds for our attempts for standardisation to increase efficiency. Other aspects might be covered mostly in externally funded projects.

4.3 Credibility

Credibility is already an important aspect of the work of the IMAGE team. For this reason, publications in scientific journals, regular contact with the IMAGE advisory board and the quality guidelines form already part of current practice. This will be continued in the future. Scientific papers are, for instance, also needed to ensure that the work can be presented in policy-relevant assessments such as those of IPCC. For the Advisory Board, earlier, a decision was made to distinguish formal evaluation and real advice. The latter can be done based on the initiative of the IMAGE leadership – and forms a means to ensure model quality. The intention is to involve the IMAGE advisory board in critical decisions at least every 2 years.

4.3.1 Developing more efficient methods for model use

Challenge and role of IMAGE

Up to now, IMAGE scenarios have been updated roughly every five years. Now that IAM scenarios are more established and widely used in reports, scientific publications, and policy documents, it is important to be up-to-date with the latest empirical data, preferably every year. Currently, updating scenarios, however, requires much time and is often combined with extensive recalibration processes.

Implementation

- *Standardise scenario process*. Therefore, the ambition is to standardise and automate the updating process to be able to update our scenarios efficiently. This process is taken into account when creating a new model framework in Python. A how-to-update-IMAGE document will be created that explains which scripts and data to use to update the model.
- *Annual or bi-annual updates*. At the moment, the focus on five-year large updates means that the process often starts from scratch. This means that much additional work is done - sometimes for relatively small changes. The proposal is to consider more often marginal, annual or bi-annual updates that concentrate on the most important changes. Such an incremental update process allows for the continuous availability of an up-to-date model framework and an efficient update process. A role in the team will be created, responsible for keeping track of relevant input data updates and organising the regular update moments. This also ensures that scenarios are more in line with the latest scientific insights. This holds for overall data input (e.g. economic development) but preferably also for more detailed data (like technology assumptions). The IMAGE team will in the coming years consider how to ensure that core assumptions are regularly evaluated.
- *Representation of costs, technologies and policies*. More and more, we would like information to be coupled to standardised data sets for technology information (costs, efficiency), model calibration and policy representation. Representation of these aspects in the model will be standardized, allowing for a more generic approach in adapting and updating the model framework and, at the same time, more efficient analyses.
- *Collaboration with other teams*: The IMAGE will actively work together with other IAM teams and the other teams within PBL (such as the national team working at climate and energy) on data inputs and updates.

The elements mentioned above are related a standardisation will allow more regular updates of scenarios. In 2022, we will organise some sessions to find out what is possible and include this better into the core IMAGE programme.

4.3.2 Model language

Challenge and role of IMAGE

Scientific computing has advanced considerably in recent years. The advent of cloud computing capabilities and the development of an ecosystem of scientific computing libraries enable potential improvements in scientific modelling infeasible within the current framework.

The Python scientific ecosystem has a wide range of open-source numerical computing libraries aimed at the scientific community. Therefore, the IMAGE team has the ambition to transition to Python.

Implementation

This transition includes the IMAGE core models and associated tools (data processing, run environment). This transition is motivated by the following four factors:

- At the moment, multiple programming languages are used. This leads to a wide required set of skills in the team. Moreover, some of the languages require additional costs for updates and licences.
- To increase model research capabilities by using powerful software in the scientific Python ecosystem.
- To improve model quality and quality assurance by providing more strict coding guidelines.
- To use open-source software and make the model framework open source available

Recently, Python has been used to create the run environment and several related tools to use Azure cloud computing. The IMAGE team will take a gradual stepwise approach to the further transition to Python in the coming years. The IMAGE Framework core models are dynamic, deterministic, continuous simulation models. The MyM language is aimed at creating time simulation models based on simple equations. We want to retain the benefits of researchers translating their expert knowledge into a model while minimising the need to spend time on the technical aspects of programming such a model. To that end, we build a Python package responsible for some of the basic modelling functionality, such as time simulation, arrays, and data and metadata handling. This can be translated into several steps:

- *Stepwise conversion to Python of TIMER, FAIR and GISMO.* The primary focus of the first phase is on stepwise converting the models and tools currently written in the MyM simulation language. Specifically, these are the TIMER, FAIR and GISMO models. Also, some other tools are MyM-based such as the IMAGE-land postprocessing tool and the Biotool. The conversion to Python will include a plan to deal with potentially increasing running times due to the language's properties. For example, this could be a challenge for FAIR, where a scenario run currently takes about 14-17 hours and could exceed 24 hours when Python is used.
- *Updating USS and TUSS.* After this, USS and TUSS scenario visualisation tools will be replaced.
- *Determining ambition for IMAGE-land*. We will analyse what form the transition of the IMAGE-land model will take. IMAGE-land is a computationally intensive model, written in FORTRAN and coupled to LPJmL (in C). It comes with specific challenges: realising a hard model coupling and achieving the required performance to do grid-based calculations.
- *Model documentation.* Many open-source, open data tasks can be automated or built-in when Python is in place, and the code is structured correctly. An example of this is the following: when IMAGE-code is well written and well structured, it contains, alongside the mathematical code, documentation with certain markers. The automatic documentation-functionality can use these markers to generate an updated IMAGE wiki-documentation with the click of a mouse.

4.3.3 Technical and methodological issues IMAGE-energy

This section includes some critical improvements in the IMAGE-energy modelling framework in addition to the priority areas already discussed under Sections 4.1 (e.g., developments in the context of net-zero emissions or material use and circularity) and 4.2 (e.g., development towards open-source code and improved response strategies and policies):

- *Electricity system.* The representation of the electricity system in TIMER is based on a simplification that uses a (residual) load curve approach. This means that the system needs input from more extensive, external electric power system models to deal with the interaction of supply and demand (and the possible issues related to system integration). The current approach cannot dynamically deal with changes in demand or with technology improvements. Moreover, the information from the extensive models is updated only every few years, which implies that we risk that IMAGE-energy can have an outdated representation of integration issues. Finally, electricity supply is expected to get increasingly integrated with other parts of the energy system, including end-use (storage options, load adjustment) and possibly hydrogen production. Therefore, it is important to improve the information on system integration and add a more dynamic representation. Given the importance of this for the overall mitigation strategy, activities are assessed to be critical.
- *Code improvement*. As indicated in 4.3.1, it is intended to transfer the IMAGE code into a Python-based system. As part of this, the model code will also be improved further - by systematically introducing standardised algorithms for specific functions such as learning, substitution and capital turn-over. We will also include automatised checks on units and documentation. These activities are deemed to be essential for further development.
- *Integration of economic modelling.* Several issues in the representation of climate policy and energy system development are directly related to broader macro-economic considerations. This includes, for instance, access to modern energy, (constraints on) investments and impacts on economic growth. To better capture these, we will integrate a small economic model in TIMER based on the existing model code developed for cost benefit analysis of climate policy (see also 4.1.1). Activities will take part first-of-all as part of external projects.
- *Downscaling.* A strength of the overall IMAGE system is the representation across different scales, i.e. global connections, 26 socio-economic regions and a detailed grid. At the moment, the IMAGE-energy system does not capture the grid level. Still, increasingly geographic issues do play a role - in system integration of renewables, access to modern energy, climate impacts and air pollution, for instance. We will develop methods to downscale the information developed at the 26 regions to the grid level and integrate this into the IMAGE-energy infrastructure. However, the downscaling activities are not critical to the IMAGE project (and are thus classified as lower priority).
- *Heterogeneity.* Heterogeneity plays a major role in sustainable development issues and climate change. This relates, for instance, to income distribution and related issues in terms of access to modern energy and distributed impacts of increased energy costs. It also relates to the different interests of actors in climate action. To deal with this, we will better represent heterogeneity in the model - by 1) introducing rural/urban income

quantities in the model where relevant, 2) calculating impacts of climate costs for these groups and 3) paying more attention to the role of different important actors in climate policy. These activities are coupled to 4.1.1 – and would allow new application options (meaning that they could potentially be done more in 'research' mode).

4.3.4 Technical and methodological issues IMAGE-land

This section includes some critical improvements in the IMAGE-land modelling framework in addition to the priority areas already discussed under Sections 4.1 and 4.2.

- *Critical evaluation of impacts and adaptation:* Specifically, climate impacts on crop yields as provided by LPJmL may be relatively optimistic as various negative processes are not represented, such as the impact of flooding, pests and some aspects of prolonged droughts. In a more flexible approach, alternative estimates of crop yield impacts at the grid level could be applied. Also, the sensitivity of natural vegetation and forestry to climate change and recovery after disturbance requires attention. This is also related to the ambitions related to climate modelling (see 4.3.5). Regarding adaptation, points of improvement will be identified where in the model either adaptation is missing despite impacts (e.g. drought-resistant crops) or where full adaptation is assumed despite potential real-world imperfections (e.g. reallocation of land and optimal irrigation levels under climate change). Evaluation of the representation of impacts and adaptation and definition of priorities will be carried out in 2022.
- *- Reducing runtime.* IMAGE-land is currently a bottleneck in the modelling train as it takes a relatively long time to run (~30 hours for the 1970-2100 period). There are various possibilities to reduce the run time that we could pursue, specifically:
    - Run LPJmL in parallel mode (on more machines than the 12 currently used). This is a relatively simple improvement as the LPJmL model is already suitable for this approach. Therefore, implementation is a high priority.
    - Start IMAGE-land runs in the scenario year from a restart file, avoiding 45 years of history. The feasibility of this development needs to be assessed before a priority decision can be made.
- *Programming Language:* IMAGE's Land Management module (the core of IMAGE-Land connected to LPJmL and MAGNET) has been programmed in Fortran, and this code has evolved for decades. This is perceived as a high barrier for new users to start coding in IMAGE-land, and the current code is currently not in a state that allows for transfer to open-source. We will explore whether a transfer from Fortran programming language towards Python could help (see also above, section 4.3.2).

Modular approach in collaboration with other institutes. The current IMAGE-land setup depends on using models from other teams, specifically LPJmL from PIK and MAGNET from WEcR. This makes it possible to use developments from other teams, increasing the number of topics our work can cover. However, it also makes the IMAGE team dependent on others' model development decisions that we do not control in LPJmL and MAGNET. Neither do we 'own' investments we make in model developments of those models. LPJmL is fully operated al PBL. However, we are not flexible and independent in applying IMAGE, including MAGNET, as we depend on capacity at WEcR to contribute. This also affects cooperation and acquisition. For LPJmL, we conclude that there is added value in having coupled hydrological-carbon-plant growth modelling and its independent use at PBL. We, therefore, argue for a continuation of using LPJmL. For MAGNET, we see great benefits in collaboration. However, a unique, own agro-economic model would allow more flexible IMAGE application and avoid competition with WEcR in the long term. Therefore, we will explore using SIMPLE-G from 2022 onwards (starting with an introductory course for several colleagues in March 2022).

4.3.5 Technical and methodological issues IMAGE-integration

We finally list a few critical issues that are related to IMAGE as a whole.

- *Run environment*. At the moment, IMAGE-land and IMAGE-energy are soft-coupled. As listed in 4.3.3, some IMAGE applications would benefit from a more direct coupling. This can be done via specific coupling software – and some tests have already been run. The priority of this activity mostly depends on specific applications that require joint evaluation of energy and land-use decisions that cannot be dealt with using the current iterations.
- *Climate model*. IMAGE uses at the moment MAGICC-6 as a climate model. Newer versions of MAGICC are available that are calibrated to CMIP6. We will update the climate model in the coming years and see whether it is possible to include MAGICC in a way that allows for faster updates (at the moment, MAGICC is recoded in IMAGE). We will also look at the downscaling procedure and the method to take climate variability into account.
- *Impacts and adaptation*. At the moment, the IMAGE model already covers climate impacts in various parts of the system (energy, land, biodiversity). We continue to represent possible climate change feedbacks on human development variables – and especially look into options to explicitly represent adaptation.
- *Cooperation with other related models in PBL*. The IMAGE forms part of a family of international models that are used within PBL, including GLOBIO (biodiversity), GLOFRIS (flooding risks), PCRGLOBWB (water). We want to continue to improve the interface between IMAGE-core, other parts of the IMAGE infrastructure and other PBL models to facilitate cooperation further. This includes, for instance, standardised data exchange.

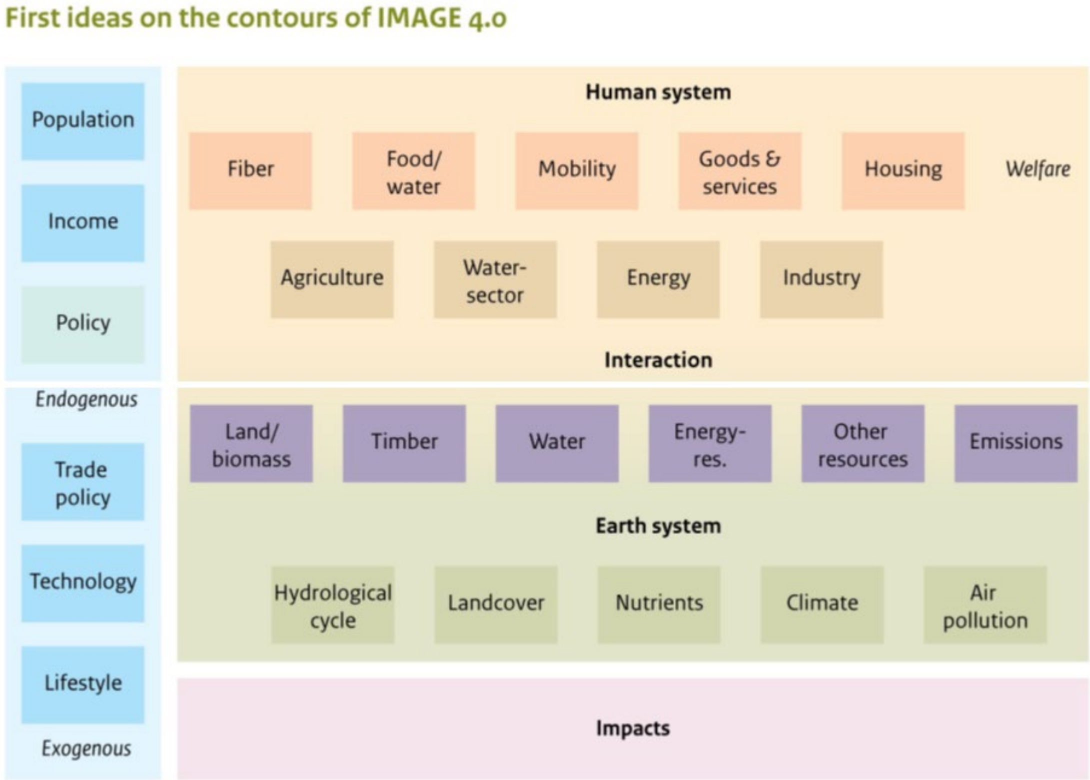
4.4 First contours of IMAGE 4.0

Over time, the focus of the IMAGE team has moved from climate change to include global environmental change and increasingly sustainable development issues. The issues discussed in Sections 4.1.1 and 4.1.3 imply a further continuation of that development: while the model's core is related to climate change and land-use change, the ambition is to relate these increasingly to sustainable development and circular economy issues. This also means that in the 2022-2027 period, we will move from the current IMAGE 3.2 model to an IMAGE 4.0 framework. The exact contours of IMAGE 4.0 are still unknown (and will be further developed and discussed in the coming years). However, some direction can already be formulated in line with the earlier discussions in 4.1 - 4.3.

Interaction of the human and earth systems. As an integrated assessment model, IMAGE will continue to focus on the human and earth systems interaction. In the representation so far, we have emphasized the critical role of the energy and land systems in these interactions. However, developments in energy and land use do not happen in isolation. First of all, there has been an increasing emphasis on the water/energy/land/climate nexus in the last few years. Furthermore, as discussed in Section 4.1, multiple claims exist for food, bioenergy, timber, and other fibres within land. Second, these systems are driven by a more fundamental demand for human services, i.e. the provision of food and water, mobility, goods and services and housing. Focusing on these services can provide better insights into material flows, ways to optimise them, and the derived demand for energy and land. In the coming years, we intend to remain relevant in the climate and land-use debate and contribute to the broader setting, as indicated in Figure 4.1.

Here, the fulfilling critical functions for human development are indicated as starting points for economic activities in agriculture, water, energy and industry. These activities interact with the Earth system via the use of resources and emissions. For the Earth system, no major updates are planned. However, this will still mean that existing models need to be updated (including MAGICC for climate; FASST for air pollution and the LPJml model. The left column indicates key drivers. The ambition is to see whether some exogenous drivers could become more endogenous in IMAGE, including population and income. However, this critically depends on model development in these areas (under 4.1.1).

Figure 4.1
Possible first sketch of the key elements included in IMAGE 4.0



Source: PBL

5 Implementation and organisation strategy

5.1 Operational issues

Quality assurance

Quality plan and implementation. Over the last ten years, the IMAGE team has introduced clear quality assurance standards for the IMAGE model. Programming guidelines have been formulated, the model couplings have been formalised and, where possible automated (1click system), and both model code and scenarios are stored in version control systems (ensuring that model results can be reproduced at any time). These efforts will be continued in the future; the IMAGE quality assurance plan will be updated in line with the PBL Quality guidelines. Specific attention should be given to ensuring that the quality guidelines are implemented, also if we are working with new staff or under time pressure. This also has implications for planning and team culture. We will encourage working in an atmosphere where it is easy to involve other team members for advice and review, even during high workloads. Both require careful planning of projects – certainly if they involve multiple team members.

Simplification. Another issue is related to complexity. Enabling the exchange of information between the various components is a considerable effort and is prone to error. Under 4.3, we formulated ambitions to improve efficiency by simplifying some of the information flows. This is a priority.

Data quality and maintenance. IMAGE is a very data-intensive model, and these data need to be maintained, documented and updated. In addition, many parts of IMAGE rely on the same or similar data, such as on population or soil properties. Therefore, additional effort will be made to use the same, most recent and best available data. However, at least as important is the consistency of the data (this refers to both the use of the same data in the model and ensuring that, for instance, the floor area data is consistent with domestic energy use data and materials used for buildings. We typically use data from various sources (emissions, land use, energy, material production, human activity) that are not necessarily fully consistent. This continues to require attention in model calibration. The IMAGE team will collaborate with other teams to set up systems for joint historical data sets.

Documentation / transparency. Model documentation and transparency has been a key part of the IMAGE strategy in the past, as illustrated by the publication of subsequent books on the model and the release of data sets. We discussed our ambitions earlier in Section 4.2 under the header of open science. One aspect is model documentation. This relates to both internal and external documentation. The model documentation on the internet (wiki) will be further developed – among other things, by providing a better link to the underlying level of the key model structure and equations. Articles describing model components, such as main references, should be added to the existing wiki and the description of new model improvements. In the next five years, we will have to evaluate the wiki platform simply due to license issues. While we want to fully preserve the current documentation functionality, we will explore alternative software environments. Equally important as the external documentation is the internal documentation. It is important to ensure that "operational manuals" and code documentation are fully up-to-date.

Multi-year programs. IMAGE was already using a long-term strategy, but planning in PBL was always done on an annual basis. PBL is now moving to a structure with multi-year programs mostly meant to steer the research agenda and increase internal cooperation. For IMAGE, there are two relevant programs: 1) international climate policy (within KLE) and 2) global environmental change (KLE and possibly other teams). The multi-year programs could help ensure continuation in research and research quality (also concerning credibility).

Introduction of new staff. It is quite a challenge for new staff to get fully operational in the IMAGE team. We have set up new methods to include new staff more easily using online lectures, buddies and formalised introduction protocols. Still, this will remain an important focus area. This also highlights the importance of model documentation, as better and more accessible documentation makes it easier for new staff to become fully operational.

External advice. The IMAGE team, in the past, contacted the IMAGE Advisory Board once every 5 to 7 years as part of the development of a new model strategy (together with the release of a major new model version). It is now recognized that it would be helpful to contact the Advisory Board regularly (e.g. once every 2 years – in various ways, such as a telephone conference). In that context, the representation of IMAGE users and funders on the Advisory Board will be improved. The Advisory Board could help IMAGE staff by advising them on model development, application, and model quality and transparency issues.

IT Support

A good functioning IT infrastructure forms a critical condition for the IMAGE team. Over the last few years, we have moved successfully to an Azure-based modelling environment, originally only as a run environment – but more recently also for general work and data storage. At the same time, this is embedded in the overall PBL infrastructure.

Management of IT infrastructure. In practice, the management of IT services for IMAGE has proven a relatively work-intensive solution requiring critical resources from the IMAGE team. Our ambition is to make the management of the work environment more professional. This means that we need more direct and more specific operational support for the IMAGE team. In principle, there are multiple scenarios to achieve this, based on a) specific capacity for model infrastructure support at the level of PBL, b) specific new capacity in the IMAGE team or c) external support (commercial company) coordinated by the IMAGE team. At this point, the third route seems most practical to implement. We will also explore whether it is possible to collaborate more directly with other modelling teams at PBL on this issue (e.g. GLOBIO).

Long-term capacity. We expect to continue to work in the Azure model environment in the 2022-2027 period. This means that funds for continuing the Azure infrastructure and IT support must be ensured for that period.

5.2 Organization

Existing situation

The IMAGE core team is housed at PBL's Department of Climate, Air and Energy (KLE). The IMAGE core team is responsible for the model quality and maintenance and leads most model development, documentation, and outreach activities. At the same time, IMAGE is also used in collaboration with several other PBL teams, mostly concerning model application (in key international projects, such as biodiversity). Main collaborating PBL departments are:

- Department of Water, Agriculture and Food (WLV). Collaboration with WLV is mainly on agricultural issues, water, emissions and nutrient flows. This involves WLV expertise used in IMAGE development and application and the use of IMAGE for WLV projects (e.g. regarding food and water).
- Department of Nature and Rural Area (NLG). Collaboration with NLG is mostly on three subjects: 1) biodiversity and the global biodiversity model GLOBIO, 2) the provision of ecosystem services, and 3) land degradation and restoration. There is a formalised linkage between the IMAGE and GLOBIO models. IMAGE regularly participates in key GLOBIO projects, and GLOBIO is used in key IMAGE projects.
- Department of Integrated Policy Analysis (IBL). The interaction with IBL mostly concerns three issues: 1) circular economy consideration, 2) impacts on human systems (GISMO), 3) uncertainty analysis.
- The national department working on energy and climate within KLE. Here, cooperation is relevant to policy and technology assumptions.
- Critical for the functioning of the IMAGE is also the IT infrastructure. For this, the support of the IT infrastructure within PBL is critical.

Outside PBL, IMAGE has been collaborating with various partners. Currently, the most important partners include:

- Utrecht University (energy system, water, nutrients, historical information): Close collaboration on model application and development with several people seconded at Utrecht University.
- WEcR (agro-economy): Cooperation regarding applying the MAGNET model as a core part of IMAGE modelling and scenario development.
- WEnR (land-use representation and hydrology): The collaboration currently concentrates on water supply, agricultural water demand and the water-food-energy nexus.
- PIK (carbon cycle, hydrology, crop modelling): PIK's LPJmL dynamic global vegetation model forms a key component of the IMAGE framework, recent collaboration mainly focused on the simulation of forest plantations.
- IAMC consortium, and specially PIK, IIASA and FEEM (cooperation strategy for European Commission projects).

- The consortium around the Agclim project has been collaborating on agriculture outlook issues.

Strengthening the cooperation network.
The Advisory Board has advised us to continue collaborating with other institutes, particularly with key partners. This is also an important strategy given the ambitions formulated in Chapter 4 and the size of the IMAGE team. Moreover, topics do get increasingly complex. In this context, we will further develop a collaboration strategy building on current network relationships. In this context, it should also be noted that the cooperation with the partners mentioned above has been successful. Most partners mentioned have expressed their interest in continuing or even strengthening the current level of collaboration.

Over the past ten years, the situation has become much more of a strategic alliance than normal cooperation concerning Utrecht University. As IMAGE team, we run projects at Utrecht University, providing us options for collaboration with teams at the UU (regarding innovation, energy technology, sustainable development) and can be more flexible in terms of contracts and funding organisations. At least for several years, several people at Utrecht University have been critical members of the IMAGE team and participate actively in IMAGE meetings, IMAGE management, application, and development. It is our ambition to continue this situation also in the future. We can also explore whether it is possible to deepen further the collaboration on topics like drivers of global environmental change, interaction with earth-system research at UU (nitrogen, water and climate), understanding historical trends in global environmental change, and future resource demand.

For the other partners, we also intend to collaborate further:

1. WEcR (agricultural demand): Mutual benefits must be reconfirmed and strengthened via joint funding. Close collaboration on subjects with complementary expertise (e.g., avoided deforestation, bioenergy, dietary change, afforestation, mitigation in agriculture).
2. WEnR: Collaboration currently concentrates on water supply and agricultural water demand; possible subjects for further collaboration are crop modelling, yield gap assessment, and response strategies for agricultural systems.
3. PIK-LPJmL: The LPJmL model from PIK forms a core element of IMAGE 3.2. Quality control, complementary expertise, and benefits for PBL and PIK need to be revisited and strengthened.
4. Long-term collaboration with PIK, IIASA and CMCC: The IMAGE team has successfully collaborated with leading integrated assessment teams in Europe in projects funded by DG Research and DG Climate. We intend to continue this collaboration. While we will also collaborate with other partners, these projects allow for further model development and model application and comparison.

This list, however, is not exclusive. In fact, for several areas, including studies on feasibility and heterogeneity, we will need to expand our list of cooperation partners further (these issues might be addressed at, e.g. Utrecht or Groningen University). However, other topics might include land degradation, model infrastructure (The Factory, Vortech), the contribution of non-state actors or health.

It should be noted that PBL will remain the ‘owner’ of the model. We will, however, allow cooperation partners to be actively involved in the overall IMAGE project under certain conditions. This also would depend on their ambition levels. A more advanced strategy of transforming IMAGE into a community model in the coming period seems to require too much workload, given the team’s current size. Independent of the level of collaboration, it is important that model improvements developed elsewhere will be subjected to adequate testing and quality control. This is included in the quality plan of IMAGE.

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Appendix

Table A.1
Interactions between the salience, legitimacy, and credibility criteria

	Salience	Legitimacy	Credibility
SDGs	Key: one of the big challenges		
Net-zero	Key: one of the big challenges	Important: representation of net-zero targets	
Materials flows	Key: one of the big challenges		Important: model development needed
Multiple claims on land	Key: one of the big challenges		Important: model development needed
Open science		Key: transparency	Important: 21st-century science
Policy	Important: only relevant when representing real-world developments	Key: stakeholder inclusion	
Python			Key: model development needed
Methodology IMAGE land			Key: model development needed
Methodology IMAGE energy			Key: model development needed