MESSAGEix-GLOBIOM: Using a full-fledged IAM

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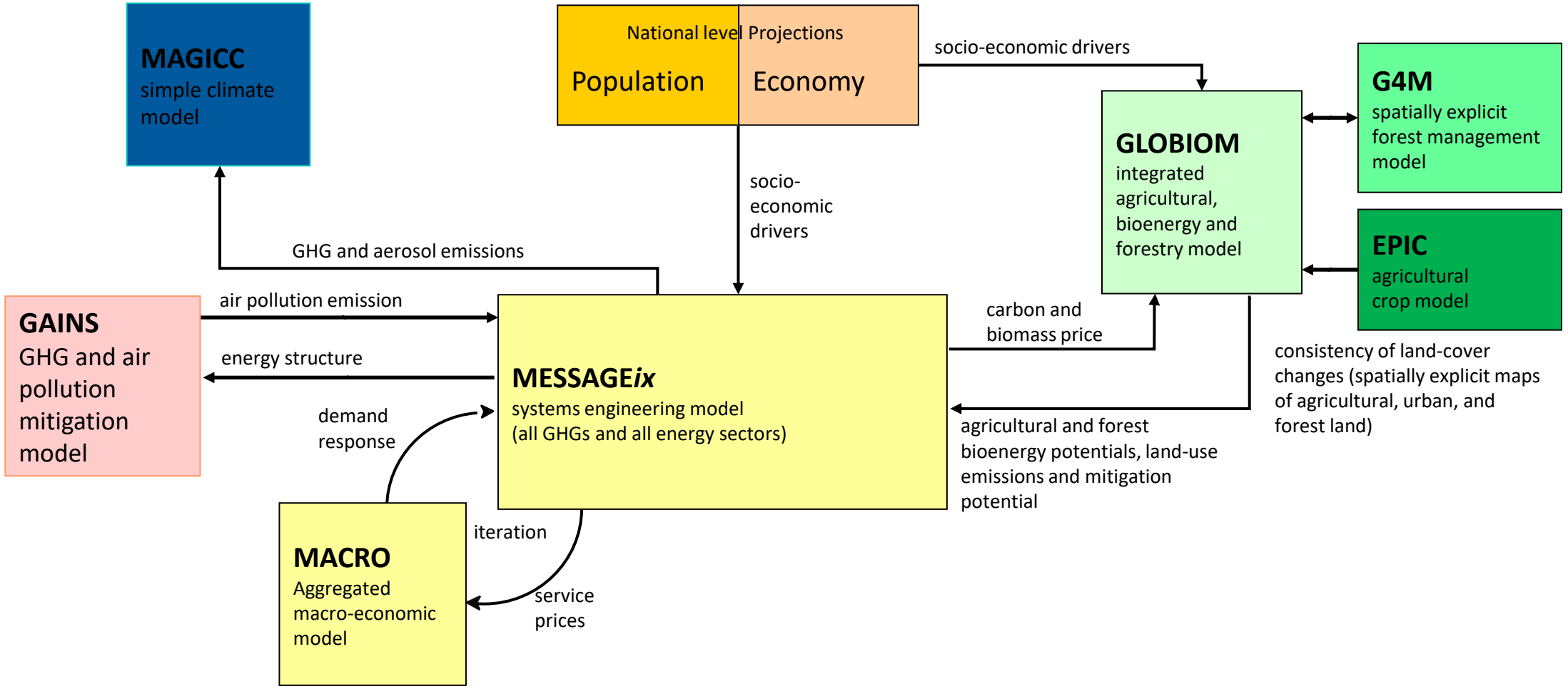
18 October 2024

NTNU course: Integrated Assessment Modelling (EP8900)

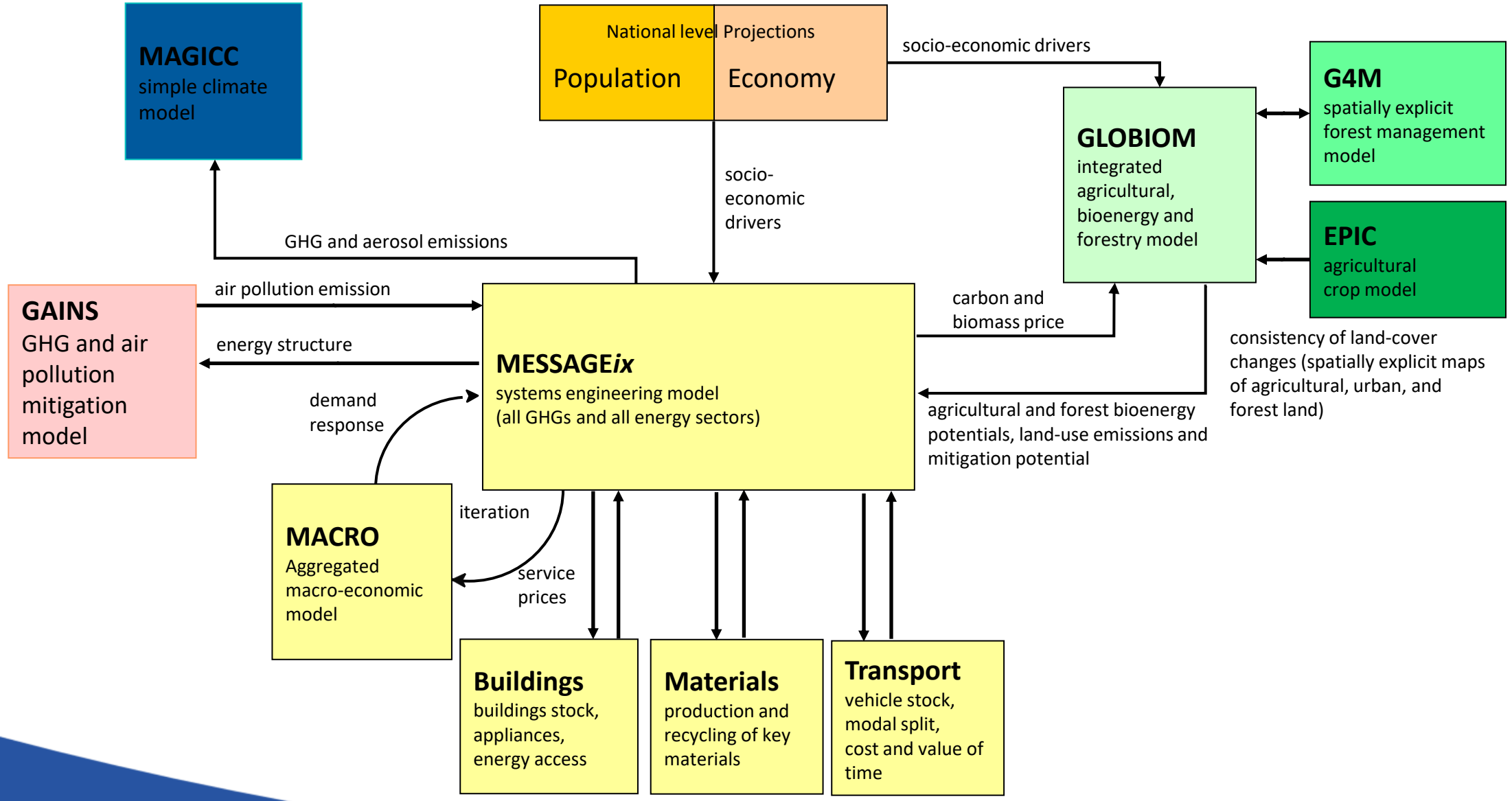
MESSAGE$_{ix}$ in brief

- **Sectors**:
  - ⇒ All energy sectors (supply & demand – with optional detailed demand-side modules)
  - ⇒ land-use representation via parametric GLOBIOM emulator
- **Regions**:
  - ⇒ global coverage, 12 regions (with flexible region aggregation depending on research needs)
- **Methodology**:
  - ⇒ Linear programming (objective: total discounted system costs)
  - ⇒ Aggregated single-sector macro-economic model (non-linear)
  - ⇒ Stock-turnover (simulation) model (building stock)
  - ⇒ Simulated structural econometrics model (cooking, household appliances)
- **Option representation:**
  - ⇒ energy-engineering model with some 400 energy technologies (excl. end-use modules)
- **Time horizon**: 2015 – 2110, 5-year time steps until 2060, then 10-year time steps
- **Foresight:** Perfect foresight; recursive-dynamic, adaptive mode possible
- **Documentation**: Krey, Havlik et al. (2020), https://docs.messageix.org/projects/global/
- **Code**: https://github.com/iiasa/message_ix (Apache 2.0 license)

MESSAGEix-GLOBIOM IAM framework



MESSAGEix-GLOBIOM IAM framework



Some historical context on MESSAGE

NOT FOR QUOTATION
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OF THE AUTHOR

A MODEL FOR ENERGY SUPPLY SYSTEMS
ALTERNATIVES AND THEIR GENERAL
ENVIRONMENTAL IMPACT

Malcolm Agnew
Leo Schrattenholzer
Alfred Voss

January 1979
WP-79-6

Working Papers are interim reports on wo
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https://pure.iiasa.ac.at/id/eprint/1177/

Addendum to:
RM-78-26

USER'S GUIDE FOR THE MESSAGE COMPUTER PROGRAM

BY

M. AGNEW, L. SCHRATTENHOLZER, AND A. VOSS

May, 1978

Research Memoranda are interim reports on research being conducted by the International Institute for Applied Systems Analysis, and as such receive only limited scientific review. Views or opinions contained herein do not necessarily represent those of the Institute or of the National Member Organizations supporting the Institute.

https://pure.iiasa.ac.at/id/eprint/971/

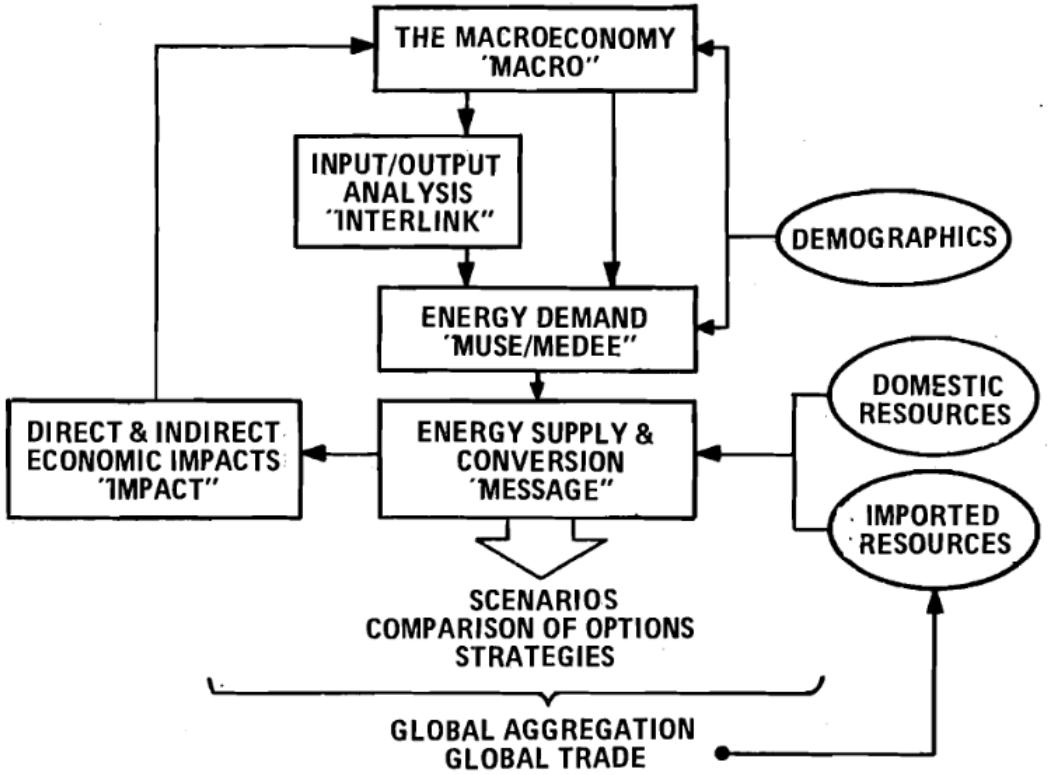
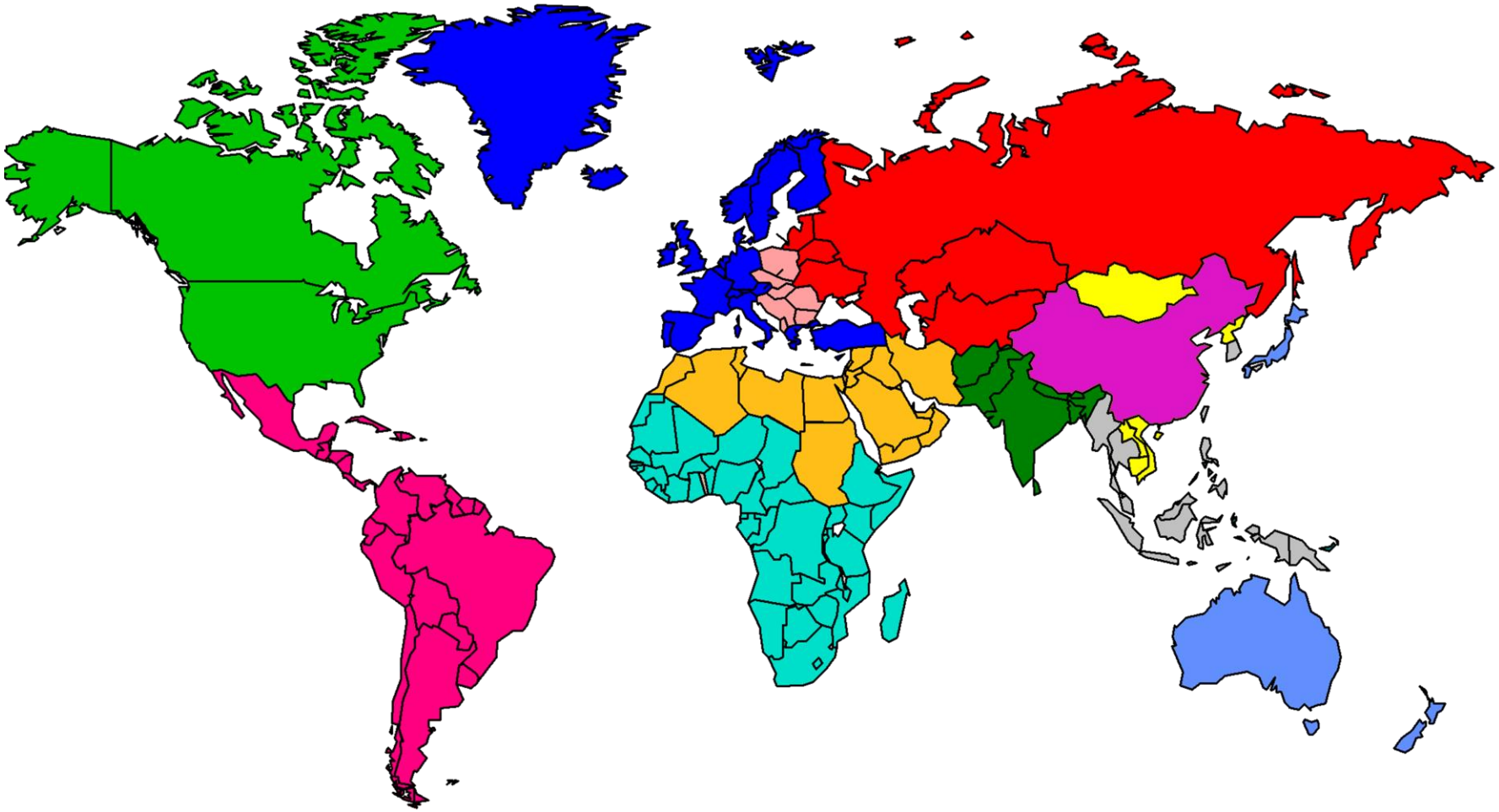


Figure 1 A profile of the IIASA set of energy models for a region

MESSAGEix: 12-17 Regions



- **NAM** North America
- **PAO** Pacific OECD
- **WEU** Western Europe
- **EEU** Central and Eastern Europe
- **FSU** Former Soviet Union
- **MEA** Middle East and North Africa
- **AFR** Sub-Saharan Africa
- **LAM** Latin America & Caribbean
- **SAS** South Asia
- **PAS** Other Pacific Asia
- **CHN** China
- **RCPA** Rest of Centrally Planned Asia

MESSAGEix infrastructure

Based on material by Siddharth Joshi, Daniel Huppmann and the MESSAGEix team

MESSAGE IX
COMMUNITY

MESSAGE$_{ix}$ modeling framework: Goals and Vision

Aim and vision of the framework as a whole

Goal: Developing a platform for streamlined modeling

⇒ building versatile & powerful **mathematical models**,

⇒ using state-of-the-art tools for **data processing**,

⇒ applying best practice of **collaborative research**

Vision:

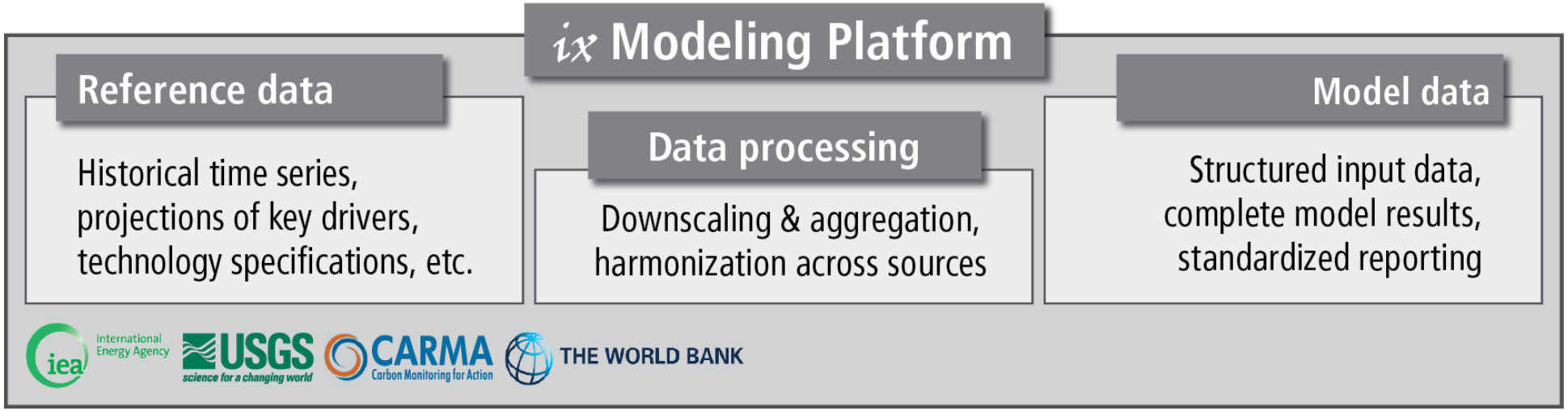
- integration of models & scientific analysis between different disciplines
- highest level of transparency and scientific reproducibility for a wide audience
- flexibility: across **spatial and temporal** levels of disaggregation

The MESSAGE$_{ix}$ modeling framework consists of a variety of different pieces

MESSAGE$_{ix}$ modeling framework: 1. Data management in *ix*mp

A central data management system (the ix modeling platform)

- An **open** platform for *i*ntegrated and *x*-cutting analysis of energy, climate, the environment, and sustainable development.



***ix*mp**, ***ix* modeling platform** or simply "**platform**" will be used interchangeably

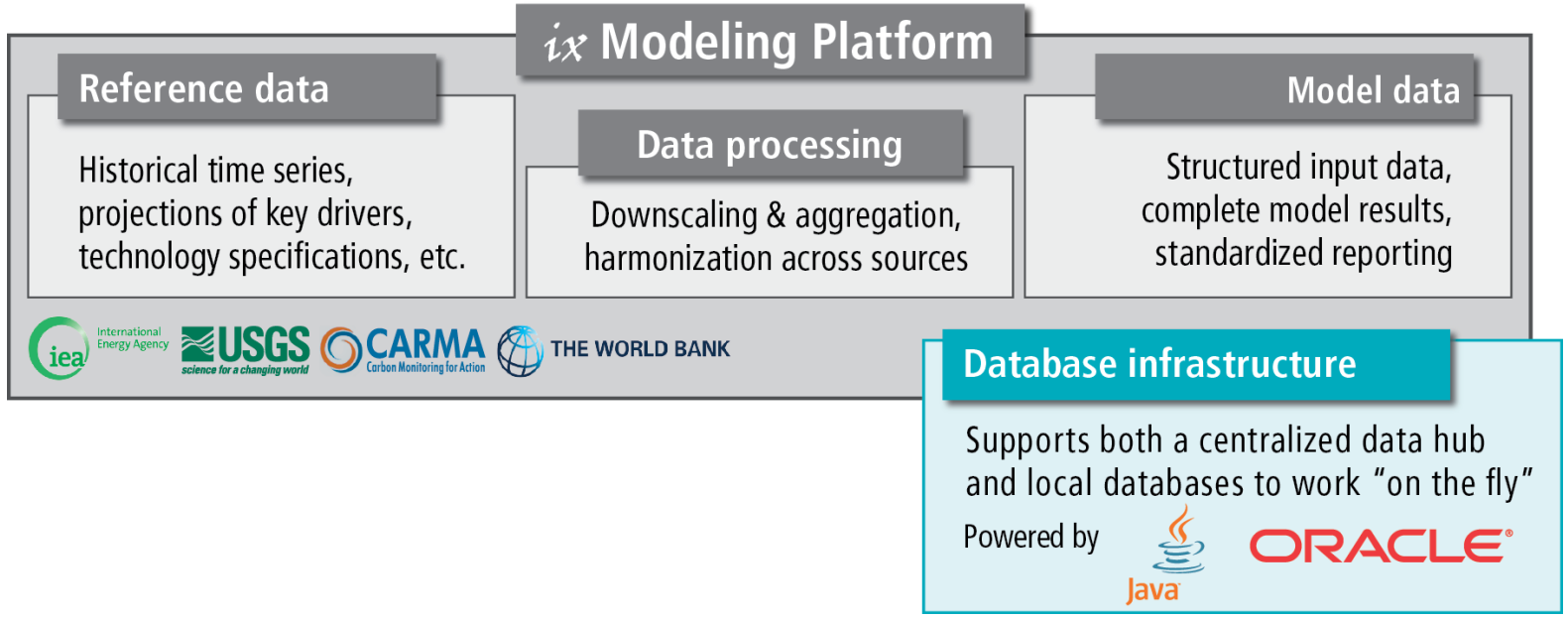
MESSAGE$_{ix}$ modeling framework: 2. Database backend

Supported by a high-performance database architecture

The platform (*ix*mp)...

... is based on a Java interface as gateway to the data

... supports both an **ORACLE database backend** for high-performance, collaborative modeling and **local, file-based databases** for getting started or working "on the fly"

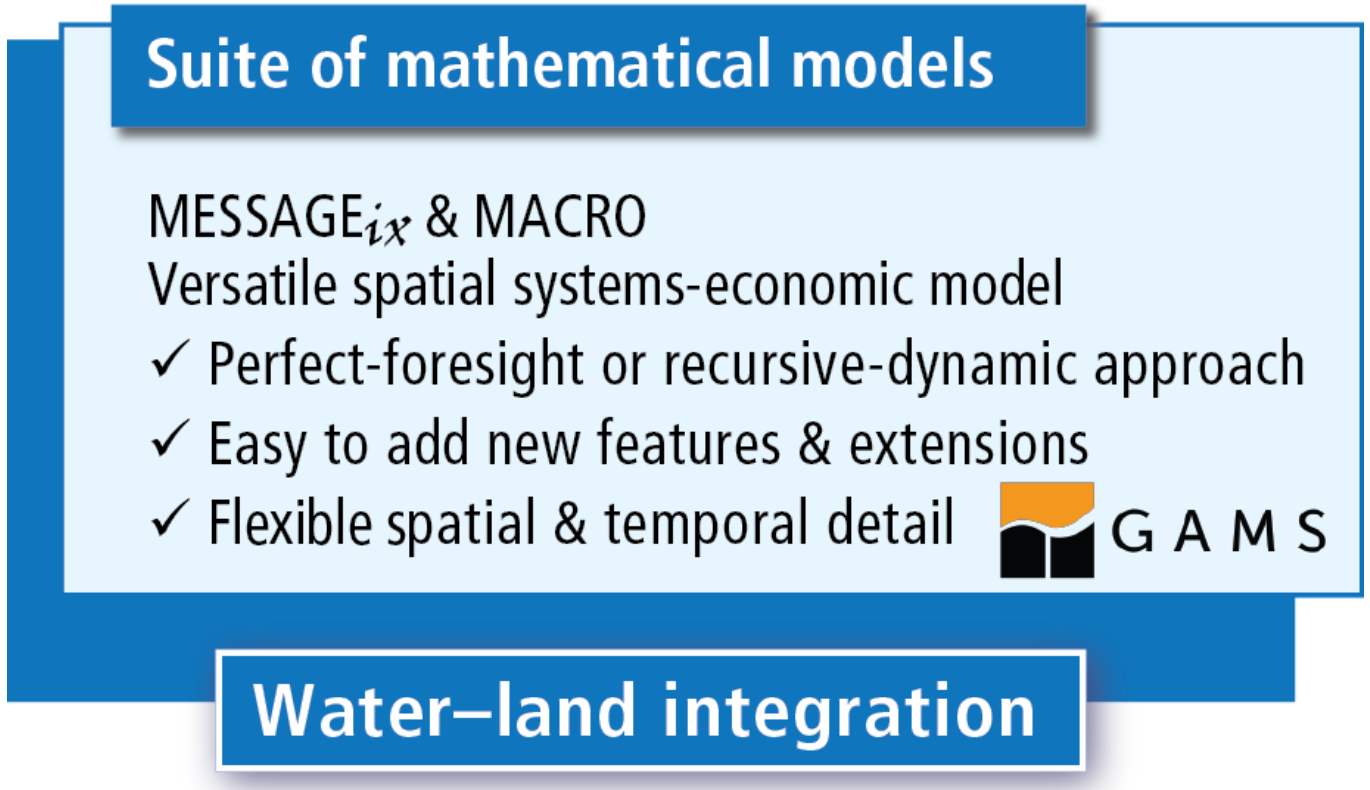


MESSAGE$_{ix}$ modeling framework: 3. Integration with GAMS

Connected to high-performance numerical programming

MESSAGE$_{ix}$ is an **Integrated Assessment Model** (IAM). Its mathematical formulation is in GAMS, a versatile software for mathematical programming & optimization.

⇒ MESSAGE$_{ix}$ is the first model fully integrated with the *ix* modeling platform (*ixmp*)



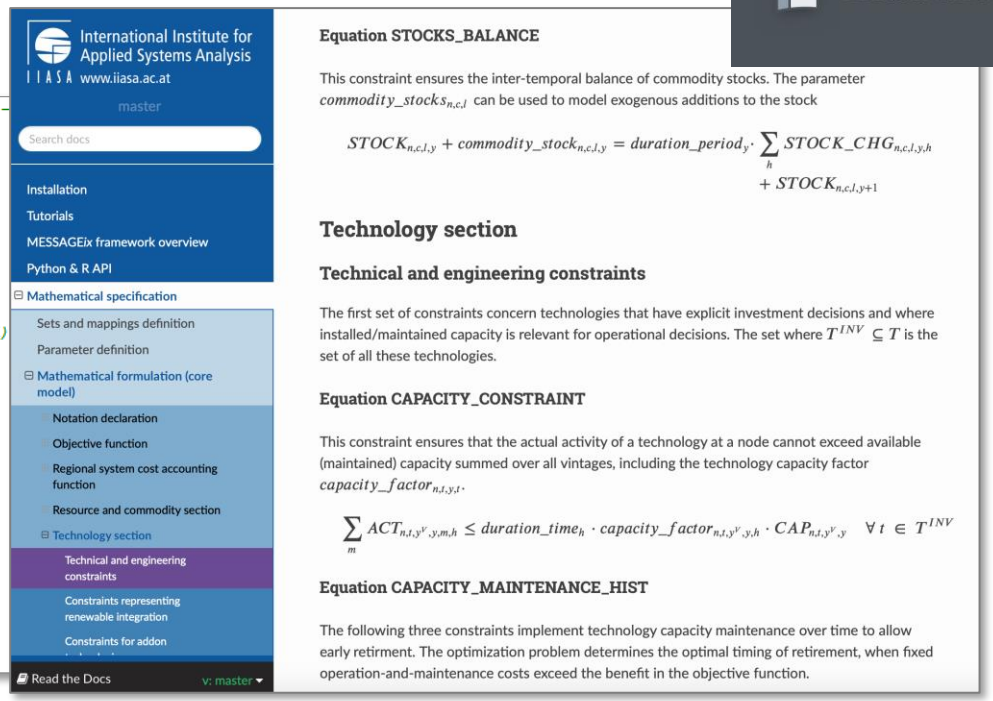
MESSAGE$_{ix}$ modeling framework: 4. Documentation

Implementing tools for comprehensive documentation

The framework ensures transparency and intelligibility
through "auto-documentation" of all codes & packages on readthedocs.com

- Documentation of all scientific programming packages using Sphinx
- Documentation of the mathematical equations generated automatically from LaTeX mark-up in the GAMS code

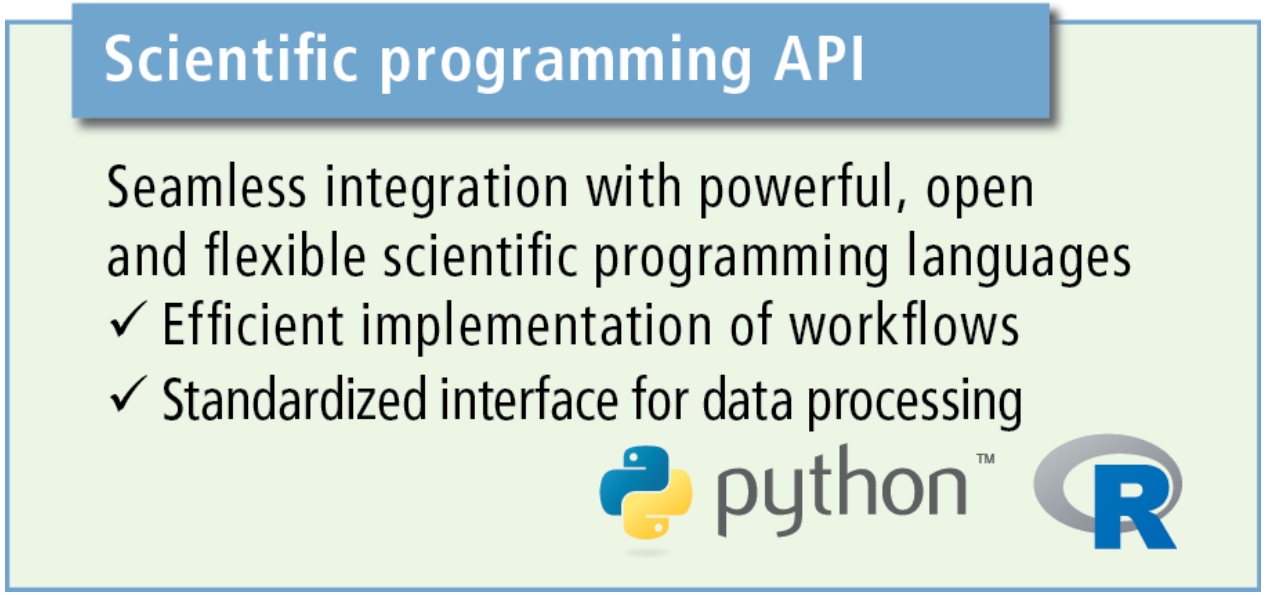
```
*---------------------------------------------------------------------------------------------------------------------
***
* Technology section
* ------------------
*
* Technical and engineering constraints
* ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
*
* Equation CAPACITY_CONSTRAINT
* """""""""""""""""""""""""""""
* This constraint ensures that the actual activity of a technology at a node/time cannot exceed available (maintained)
* capacity summed over all vintages, including the technology capacity factor :math:`capacity\_factor_{n,t,y,t}`.
*
*  .. math::
*     \sum_{m} ACT_{n,t,y^V,y,m,h}
*         \leq duration^H_{h} \cdot capacity\_factor_{n,t,y^V,y,h} \cdot CAP_{n,t,y^V,y}
*         \quad t \ \in \ T^{INV}
*
* where :math:`T^{INV} \subseteq T` is the set of all technologies
* for which investment decisions and capacity constraints are relevant.
***
CAPACITY_CONSTRAINT(node,inv_tec,vintage,year,time)$( map_tec_time(node,inv_tec,year,time)
        AND map_tec_lifetime(node,inv_tec,vintage,year) )..
    sum(mode$( map_tec_act(node,inv_tec,year,mode,time) ), ACT(node,inv_tec,vintage,year,mode,time) )
        =L= duration_time(time) * capacity_factor(node,inv_tec,vintage,year,time) * CAP(node,inv_tec,vintage,year) ;
```



MESSAGE$_{ix}$ modeling framework: 5. Scientific programming

Interfaces to scientific programming for advanced users

Python and R **Application Programming Interfaces** (APIs)



MESSAGE$_{ix}$ modeling framework: 6. Collaborative research

Geared towards best-practice in collaborative research

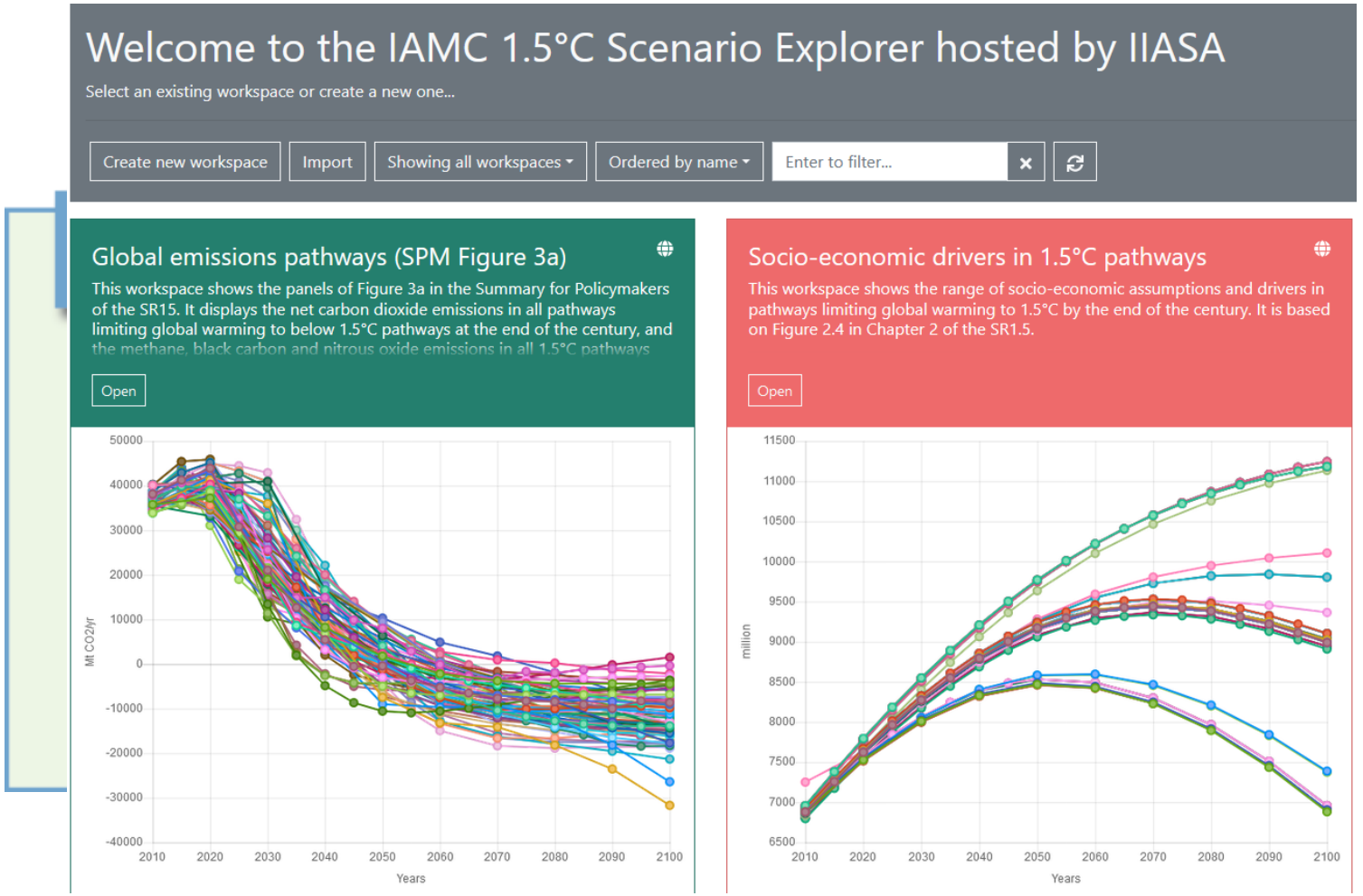
The modeling framework facilitates collaborative model development through comprehensive **version control** of data, model codes and scripts.

All contents of both MESSAGE$_{ix}$ and *ix*mp are **open-source** and online as GitHub repositories:

- https://github.com/iiasa/message_ix
- https://github.com/iiasa/ixmp/
- https://github.com/iiasa/message-ix-models (package that provides tools for research using the MESSAGE$_{ix}$ -GLOBIOM family of models)

MESSAGE$_{ix}$ modeling framework: 7. Interactive web user interface

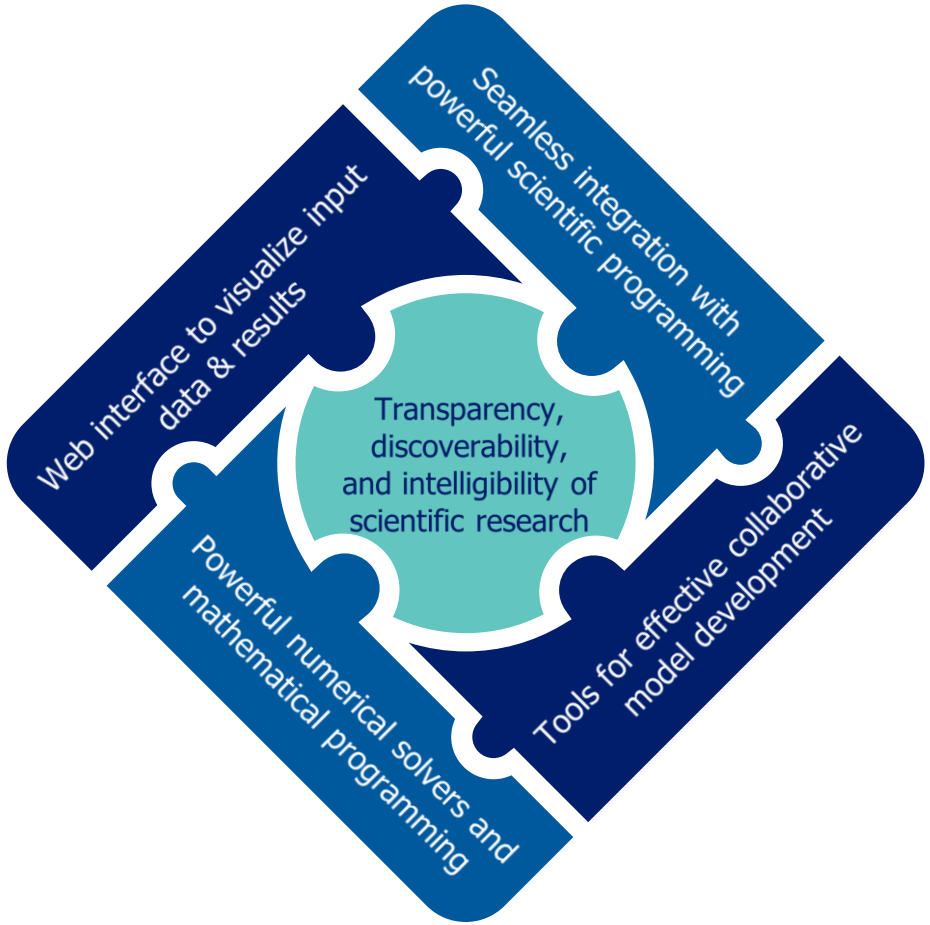
An intuitive gateway to modeling data for researchers and a wider audience

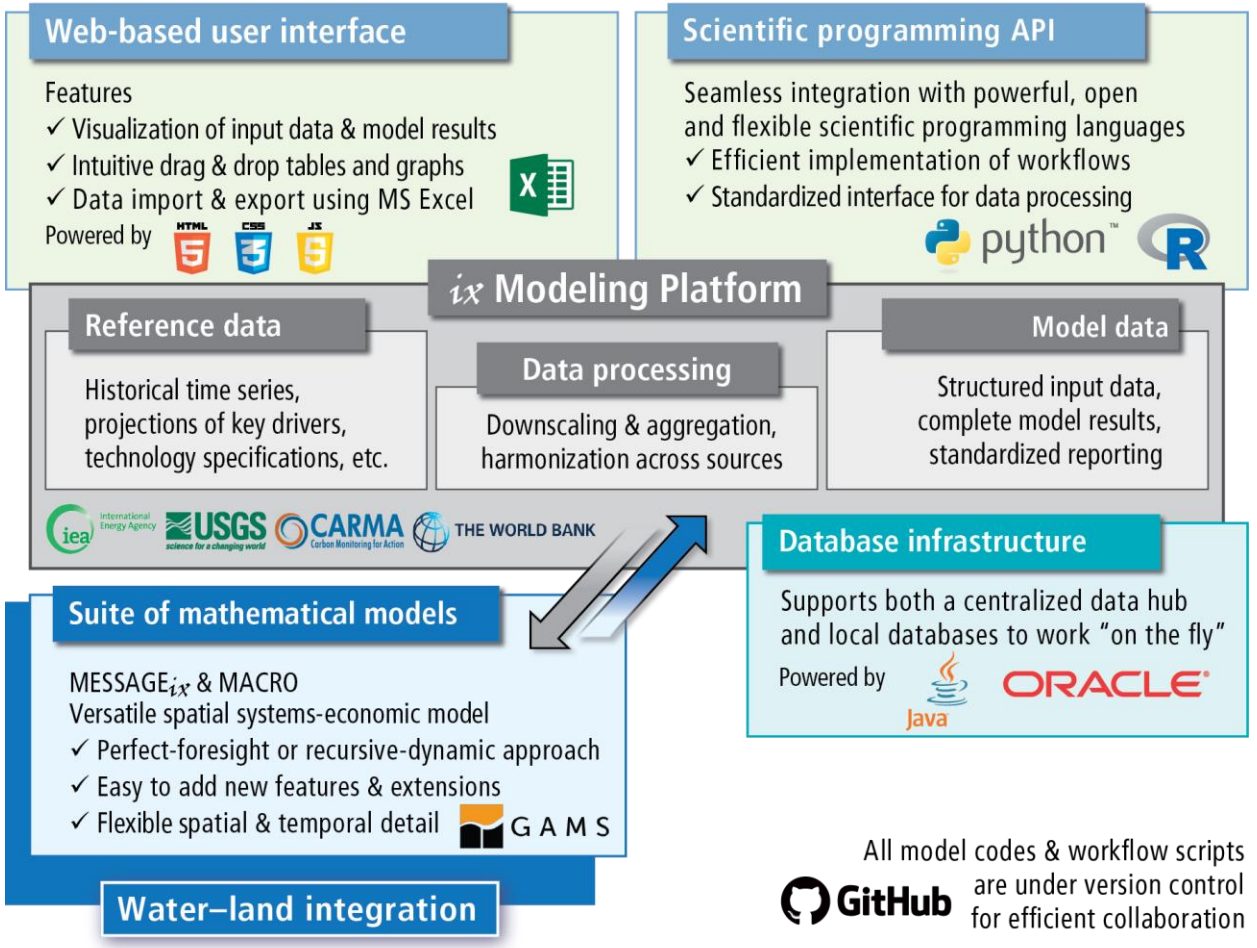


The Scenario Explorer allows for the re-use of scenario data by other research communities

MESSAGE$_{ix}$ modeling framework: Overview

Facilitating transparency and reproducibility of research





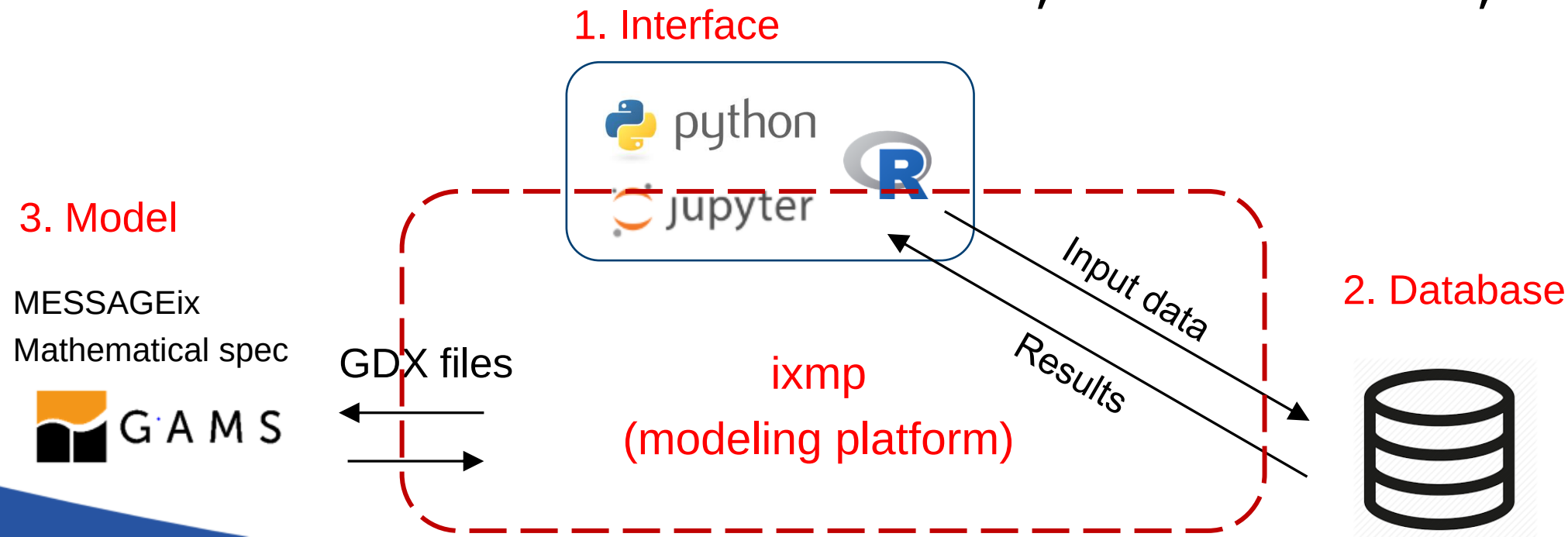
Key features of the *ix* modeling platform (*ixmp*)

(Huppmann et al. 2019)

MESSAGE$_{ix}$ modeling framework: Simplistic workflow of modeling

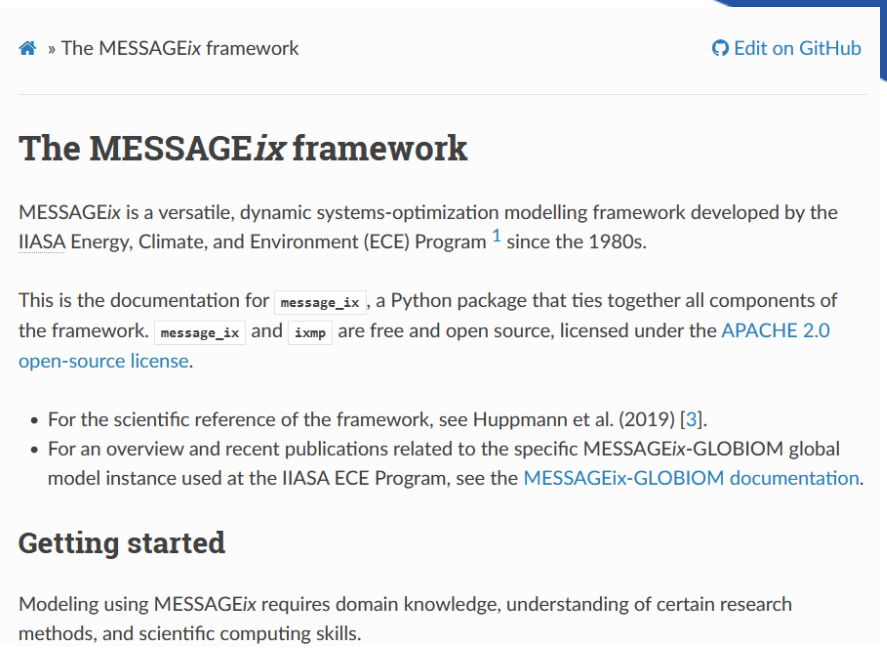
Flexible and high-performance processes

- Interface a ***central place*** for creating, loading, or working with a scenario
- Data can be modified through the interface or other input files (e.g., Excel)
- Model data and results: loaded from database, model GDX files, etc.



MESSAGE$_{ix}$ modeling framework: Main sources of information

- Main page in ReadTheDocs: https://docs.messageix.org/en/stable/
- Open-source GitHub repository: https://github.com/iiasa/message_ix (contribution guide)
- Files for the tutorials can also be found online: https://github.com/iiasa/message_ix/tree/master/tu
- Zenodo community (data and code releases): https://zenodo.org/communities/message-ix/



message-ix-models (only relevant for MESSAGE$_{ix}$-GLOBIOM):

- Main page in ReadTheDocs:
  - https://docs.messageix.org/projects/models/en/latest/
- Open-source GitHub repository:
  - https://github.com/iiasa/message-ix-models
- Qualitative model description
  - https://docs.messageix.org/projects/models/en/latest/global/index.html

For more detailed information on ixmp:

- Main page in ReadTheDocs:
  - ⇒ https://docs.messageix.org/projects/ixmp/en/stable/
- Open-source GitHub repository:
  - ⇒ https://github.com/iiasa/ixmp/

The MESSAGE$_{ix}$ modeling framework: Prerequisites

MESSAGE$_{ix}$ & ixmp, encapsulated as two Python packages

`message_ix`
`ixmp`

The workshop is designed to be accessible for participants with different backgrounds and levels of experience with the modeling. However, there are some pre-requisite knowledge and skills, including:

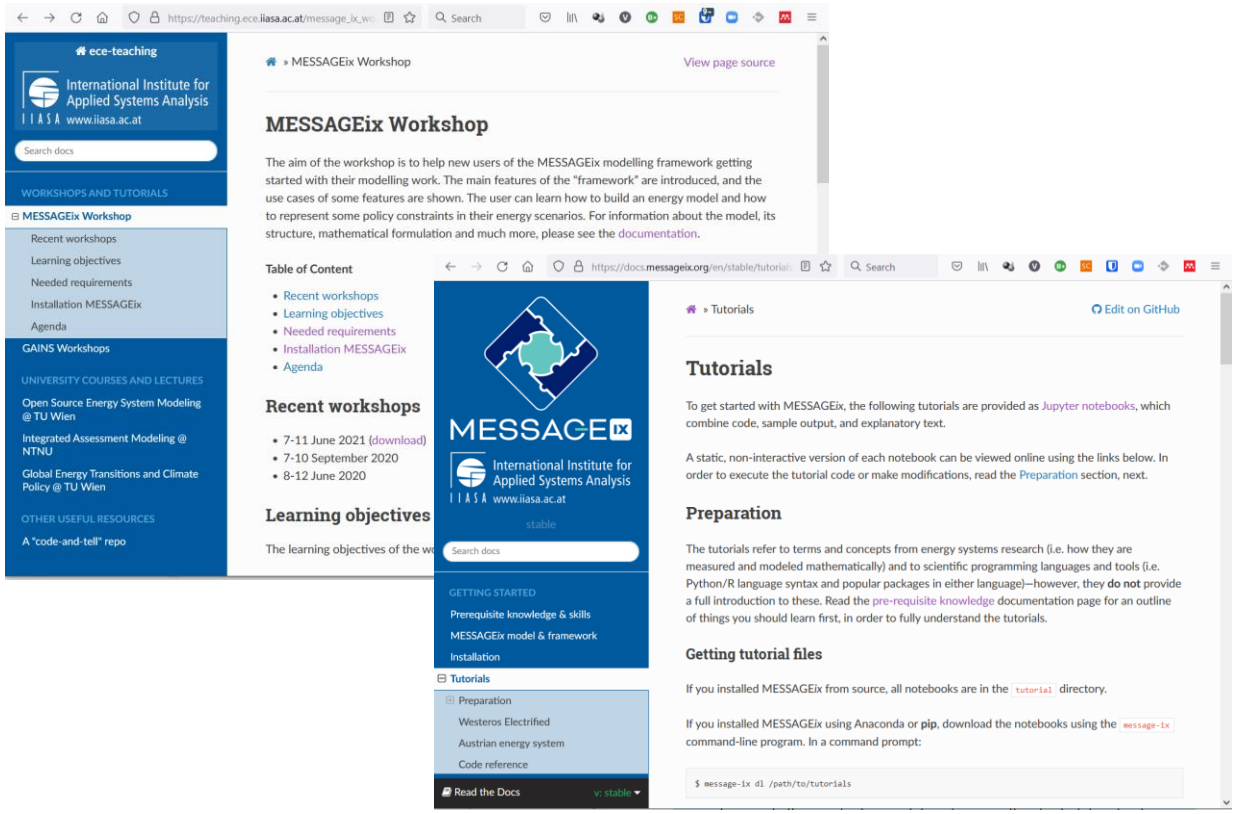
- Elementary computer programming (preferably in the Python or R language)
  - ⇒ especially, basic knowledge of **pandas**, a Python package for data analysis (pandas tutorials);
- Fundamental concepts of mathematical modeling, optimization, and linear programming;
- Energy systems (e.g., energy supply, energy conversion technologies, and demand sectors and their linkages) also energy levels and techno-economic parameters

For a complete list, plus links to learning resources, see "Pre-requisite knowledge & skills" in the documentation

MESSAGE$_{ix}$ Capacity and Community Building

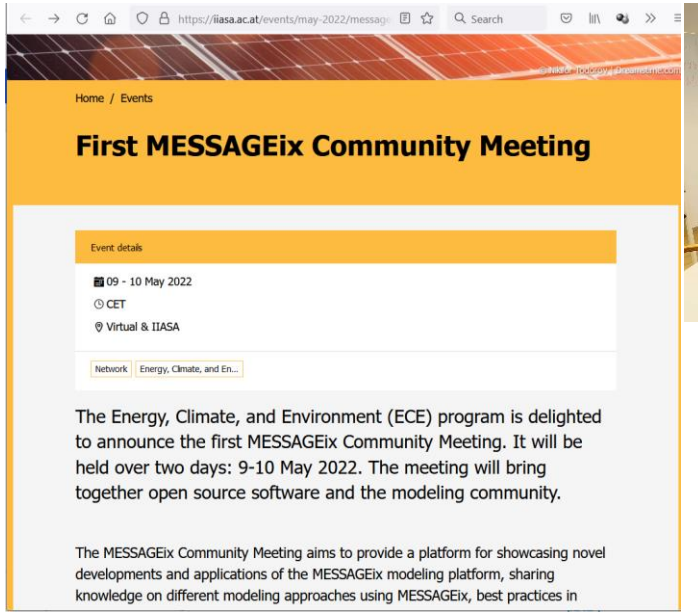
MESSAGEix Training Workshops (1-2 per year, ~25-45 participants)

- Systematic approach and material



MESSAGEix Community Meeting (annual, ~50-60 participants)

- Share modeling experience
- Generate synergies and bring back benefits to IIASA



Hybrid meeting with about 20 on-site and 40 remote participants

https://teaching.ece.iiasa.ac.at/message_ix_workshop.html https://iiasa.ac.at/events/may-2024/messageix-community-meeting-2024

MESSAGEix infrastructure

Based on material by Siddharth Joshi, Daniel Huppmann and the MESSAGEix team

MESSAGE IX
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Supplementary materials

MESSAGEix-GLOBIOM: further reading

- Documentation of MESSAGEix and ixmp
- MESSAGEix training-workshop material
- Documentation of MESSAGEix-GLOBIOM
- SSP-related MESSAGE-GLOBIOM – SSP2
- IAMC Wiki for an overview of various integrated assessment models

Data sources – MESSAGEix-GLOBIOM (Resources)

Sector	Sources
Resources: Fossil	BGR: Federal Institute for Geosciences and Natural Resources (https://www.bgr.bund.de/EN/Themen/Energie/energie_node_en.html) USGS: The U.S. Geological Survey (https://www.usgs.gov/energy-and-minerals/energy-resources-program/science/energy-resources) Rogner et al. 1997: https://doi.org/10.1146/annurev.energy.22.1.217
Resources: Nuclear	Rogner et al. 2012: https://previous.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/Chapter7.en.html Riahi et al. 2012: https://previous.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/Chapte17.en.html
Resources: Non-Biomass Renewables	NREL: U.S. National Renewable Energy Laboratory (https://www.nrel.gov/grid/data-tools.html) Rogner et al. 2012: https://previous.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/Chapter7.en.html
Resources: Biomass	Fricko et al. 2017: (https://doi.org/10.1016/j.gloenvcha.2016.06.004) GLOBIOM (https://iiasa.github.io/GLOBIOM/) GLOBIOM Lookup-tables (https://github.com/iiasa/GLOBIOM-G4M_LookupTable)

Data sources – MESSAGEix-GLOBIOM (Energy Conversion)

Sector	Sources
Renewable integration	Johnson et al. 2016 (https://doi.org/10.1016/j.eneco.2016.07.010)
Historical activity	IEA-WEB, 2017 (https://www.iea.org/data-and-statistics/data-product/world-energy-balances)
Historical capacity	Platts, 2016 (https://www.spglobal.com/) Carma, 2016 (https://www.cgdev.org/topics/carbon-monitoring-action) Raptis, 2015 (https://doi.org/10.1016/j.energy.2015.12.107)
CO2 transmission and distribution	Koelbl et al, 2014 (http://dx.doi.org/10.1016/j.ijggc.2014.04.024) Budinis, 2018 (doi:10.1016/j.esr.2018.08.003)
Investment costs	IEA-WEO, 2018 (http://www.worldenergyoutlook.org) IEA, 2016 (https://www.iea.org/media/weowebsite/energymodel/WEO_2016_PG_Assumptions_NPSand450_Scenario.xlsb) EIA, 2020 (https://www.eia.gov/outlooks/aeo/assumptions/pdf/liquidfuels.pdf) EIA, 2015 (https://www.oecd-nea.org/ndd/pubs/2015/7057-proj-costs-electricity-2015.pdf) REN21, 2019 (https://www.ren21.net/wp-content/uploads/2019/05/gsr_2019_full_report_en.pdf) REN21, 2017 (https://www.ren21.net/wp-content/uploads/2019/05/GSR2017_Full-Report_English.pdf) IRENA, 2018 (https://www.irena.org/publications/2019/May/Renewable-power-generation-costs-in-2018) IRENA, 2012 (https://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-biomass.pdf) IVL, 2015 (https://www.ivl.se/download/18.7e136029152c7d48c202a1d/1465298345076/B2221.pdf) JRC, 2018 (https://publications.jrc.ec.europa.eu/repository/bitstream/JRC109894/cost_development_of_low_carbon_energy_technologies_v2.2_final_online.pdf) IEA 2019 (https://webstore.iea.org/download/summary/2803?fileName=English-Future-Hydrogen-ES.pdf)

Data sources – MESSAGEix-GLOBIOM (Drivers)

Sector	Sources
GDP Historical	World Bank, 2012 (https://doi.org/10.1596/978-0-8213-8985-0)
GDP Trajectory	Dellink, 2015 (https://doi.org/10.1016/j.gloenvcha.2015.06.004)
Population Historical	UN, 2010 (https://www.un.org/en/development/desa/population/publications/pdf/trends/WPP2010/WPP2010_Volume-I_Comprehensive-Tables.pdf)
Population Trajectory	KC and Lutz, 2014 (https://doi.org/10.1016/j.gloenvcha.2014.06.004)

Data sources – MESSAGEix-GLOBIOM (Emissions)

Sector	Sources
CO2 fossils	IPCC, 2016 (http://www.ipcc-nggip.iges.or.jp/public/gl/invs5a.html)
CO2 extraction process	McJeon, 2014 (https://doi.org/10.1038/nature13837)
Air pollution (SO2, NOx, NH3, VOC, PM, CO, OC,	Rao et al., 2016 (https://doi.org/10.1016/j.gloenvcha.2016.05.012) GAINS (https://doi.org/10.1016/j.envsoft.2011.07.012)
Non-CO2 emissions	Rao et al., 2006 (https://www.jstor.org/stable/23297081)
HFCs historical	EPA, http://www.epa.gov/climatechange/EPAactivities/economics/nonco2projections.html
HFCs future split	Velders et al., 2015 (https://doi.org/10.1016/j.atmosenv.2015.10.071)
Forest Burning emissions historical	RCPs (https://sedac.ciesin.columbia.edu/ddc/ar5_scenario_process/reference_resource.html)
Savannah Bruning emissions historical	RCPs(https://sedac.ciesin.columbia.edu/ddc/ar5_scenario_process/reference_resource.html)
CH4 Waste (landfills and Sewage) historical	EPA, 2013 (https://www.epa.gov/sites/default/files/2016-06/documents/mac_report_2013.pdf)
CH4 Fugitive emissions	EPA, 2013 (https://www.epa.gov/sites/default/files/2016-06/documents/mac_report_2013.pdf)
SF6 historical	EDGAR4.2, 2011 (http://edgar.jrc.ec.europa.eu)
CH4 land-use abatement (enteric fermentation and manure)	EPA, 2006 (n/a)

Data sources – MESSAGEix-Buildings (STURM/CHILLED)

Category	Parameters	Sources
Demographics and socio-economics	Population, Urbanization, GDP, Inequality	SSP Database (Riahi et al., 2018)
	Household size	Database (UN 2019)
Climate	Temperatures, Solar irradiation	EWEMBI Database (Lange, 2019)
Building characteristics	Share of housing types, floorspace per capita, connection to district heating, air-conditioning ownership	Household survey data* Literature (Fishman et al.; Harvey 2014; McNeil and Letschert 2008; Isaac and van Vuuren 2009)
	Share of slums	Database (World Bank, 2020)
Techno-economics	Building lifetime	Literature (Deetman et al., 2020)
	U-values	Literature (Edelenbosch et al., 2021)
	Heating/cooling system efficiency	Literature (IEA 2018; Levesque et al. 2018; Knobloch et al. 2019)
	Investment costs, intangible costs, discount rates	Literature (Giraudet et al. 2012; Fleiter et al. 2016; Esser et al. 2019; Mastrucci and Rao 2019, Poblete-Cazenave et al. 2021)
Behaviour	Set point for heating / cooling	Household survey data*, literature (Jones et al. 2015)

*Microdata for representative countries by microregion.

Data sources – MESSAGEix-Materials

Sector	Sources
Aluminum	International Aluminum Institute (https://alucycle.world-aluminium.org/public-access/) World Mineral Production (https://www2.bgs.ac.uk/mineralsuk/download/world_statistics/2010s/WMP_2014_2018.pdf) IEA Energy Technology Transitions for Industry,2008
Steel	OECD steelmaking capacity database (https://stats.oecd.org/Index.aspx?datasetcode=STI_STEEL_MAKINGCAPACITY), World Steel Association (https://www.worldsteel.org/en/dam/jcr:0474d208-9108-4927-ace8-4ac5445c5df8/World+Steel+in+Figures+2017.pdf), Energy technology transitions for industry (IEA, 2009), ETSAP - Technology Brief I02 (IEA , 2010)
Cement	Cement Statistics and Information (USGS) (https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-cement.pdf) 2019 Activity Report (Cembureau) (http://www.cembureau.eu/media/clkdda45/activity-report-2019.pdf) Modeling Guide for the Cement Industry (ADVANCE, 2016) Voldsund, M. et al. (2019) Comparison of Technologies for CO2 Capture from Cement Production—Part 1: Technical Evaluation. Energies, 12(3), 559. https://doi.org/10.3390/en12030559 Gardarsdottir, S. et al. (2019) Comparison of Technologies for CO2 Capture from Cement Production—Part 2: Cost Analysis. Energies, 12(3), 542. https://doi.org/10.3390/en12030542 Methodology for the free allocation of emission allowances in the EU ETS post 2012 (Ecofys, 2009) ETSAP - Technology Brief I03 (IEA , 2010)
Petro-chemicals	IEA The Future of Petrochemicals 2018, New Technology Perspectives 2020, IEA ETSAP Bioethylene Production, Energy Technology Transitions for Industry 2008
Power sector	Lifecycle assessment data of material demands for power sector (Arvesen et al., 2018) https://doi.org/10.1016/j.envsoft.2017.09.010

Data sources – MESSAGEix-Transport

Category	Sources
Total passenger & freight activity projections	Literature (Schäfer et al., 2006) Transport Futures scenarios Socio-demographic drivers (e.g. population, GDP, urbanization) from SSP database, or alternately, SHAPE, GEA, NAVIGATE, and other projects.
Technology efficiencies and costs	MA^{3}T (U.S. DoE ORNL), US-TIMES. IEA. Global Fuel Economy Initiative.
Behavioural parameters for light-duty vehicle user	MA^{3}T. IIASA ECE global mobility survey.