The MESSAGE$_{ix}$ modeling framework: Building a simple Energy System Model

Volker Krey

Material courtesy of Behnam Zakeri and Daniel Huppmann

NTNU course: Integrated Assessment Modelling (EP8900)

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A tutorial to the MESSAGEix framework

Agenda

- Introduction to MESSAGEix framework
- Review of installation
- MESSAGEix model and its structure
- Working with MESSAGEix tutorials (sample models)

After this tutorial

The goal is to…

- Learn about the main component of the MESSAGEix framework
- Be able find relevant information about MESSAGEix
- Be able to create a MESSAGEix scenario, solve and plot it using online tutorials
- Learn about some important methods for data handling and scenario analysis

Requirements

- Knowledge on data analysis and programming

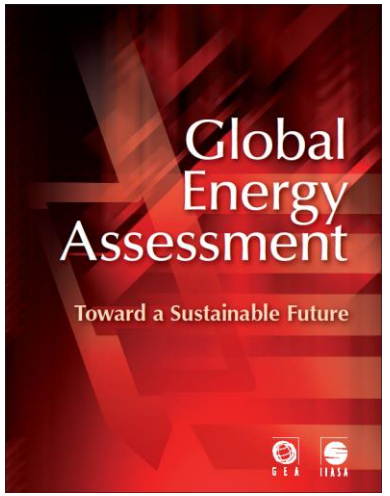
- Knowledge on energy systems
- Patience, motivation, and curiosity

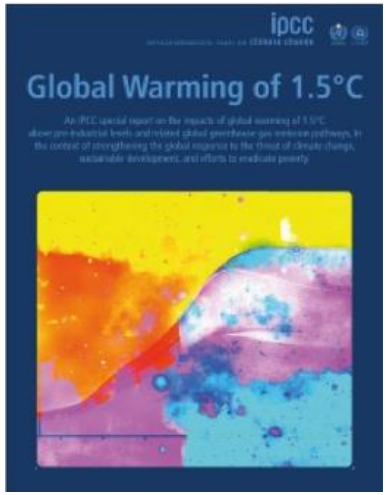
The MESSAGE model at IIASA

IIASA and MESSAGE are at the center of global energy policy assessment

- Since 1980s used for assessing sustainable development and energy/climate policies at regional and global scales

  (Manfred Strubegger, Sabine Messner and many others)
- MESSAGE a systems engineering, dynamic optimization model
- MESSAGE widely in use in other organizations like IAEA and member countries





http://www.ipcc.ch/report/sr15/)

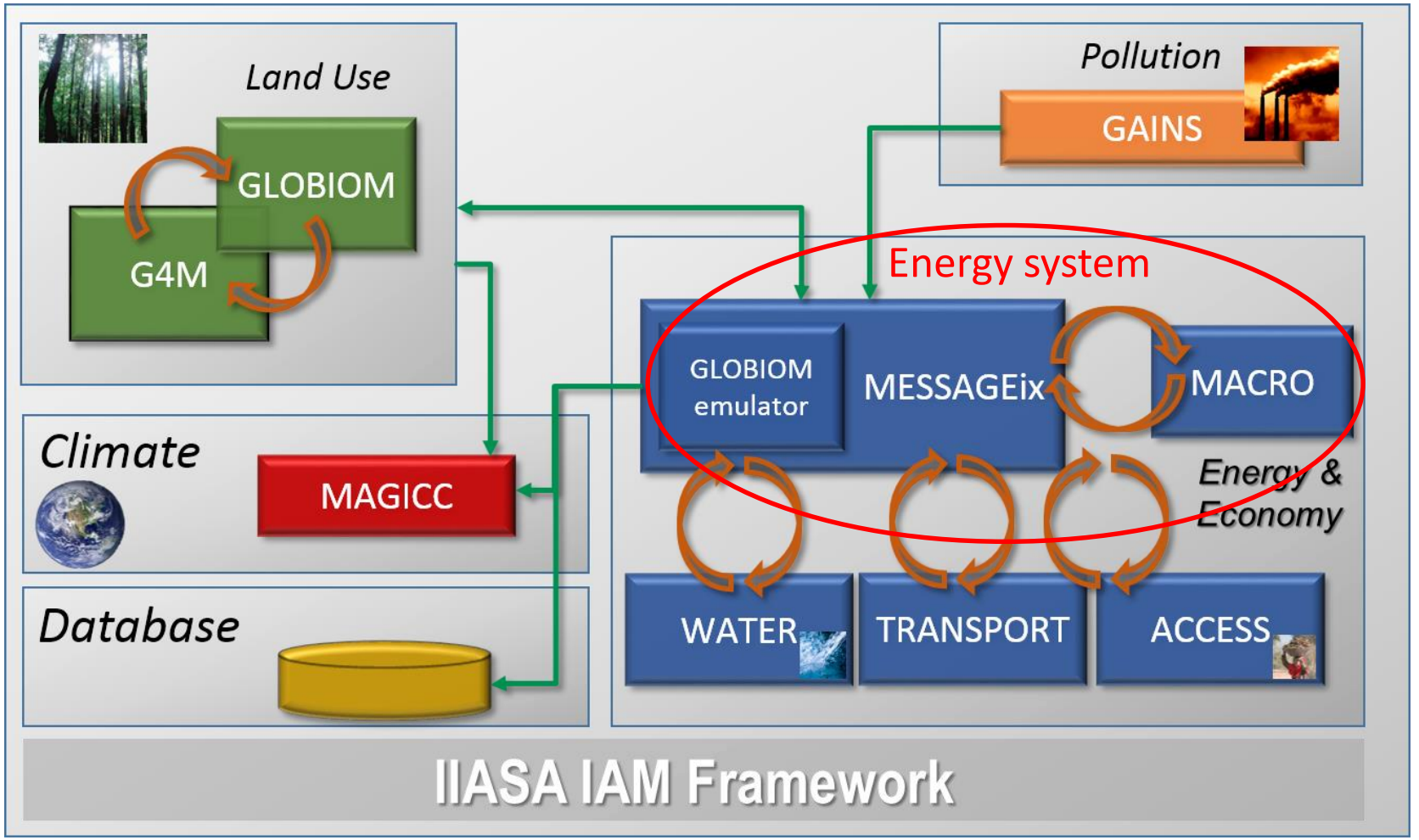
- Recent publications:

  ⇒ *A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies.* Grubler et al., Nature Energy (2018)

  ⇒ *Energy investment needs for fulfilling the Paris Agreement and achieving the SDGs*. McCollum et al., Nature Energy (2018)

IIASA's Integrated Assessment Model (IAM)

MESSAGEix is at the core



Modeling and Model Development (2)

Discussion in group: what do we expect from a good model?

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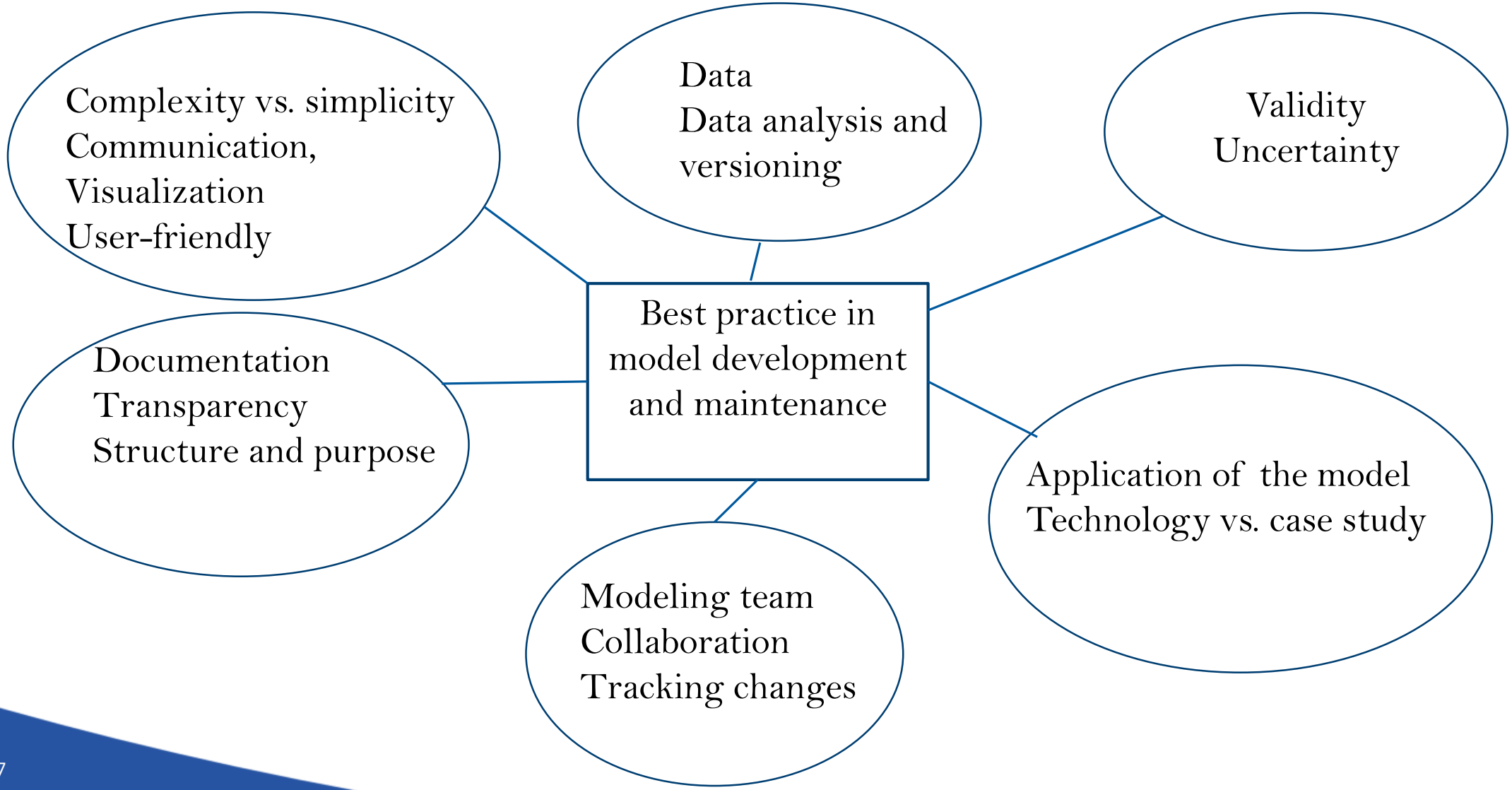
Discussion in group: what do we expect from a good model?



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

An integrated modeling platform for cross-cutting analysis

Goal: Developing a platform for streamlined modeling

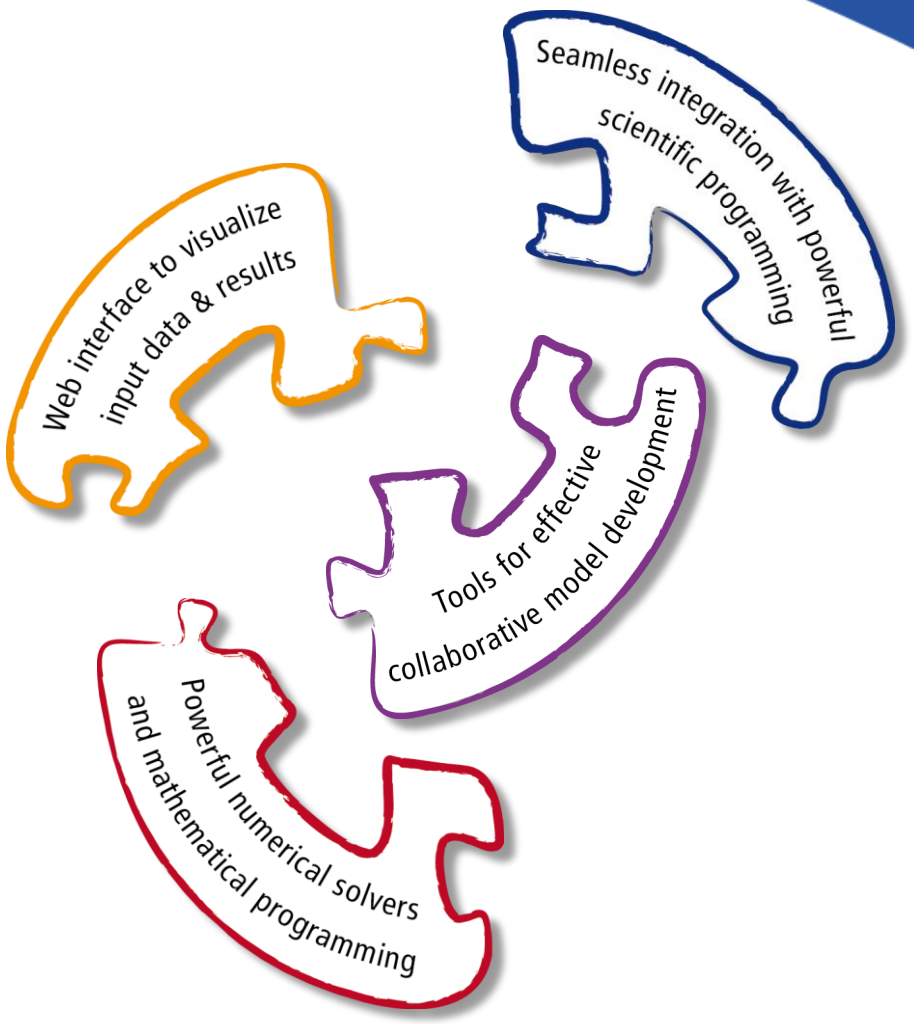
⇒ using state-of-the-art tools for **data processing**,

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

⇒ applying best practice of **collaborative research**

Vision:

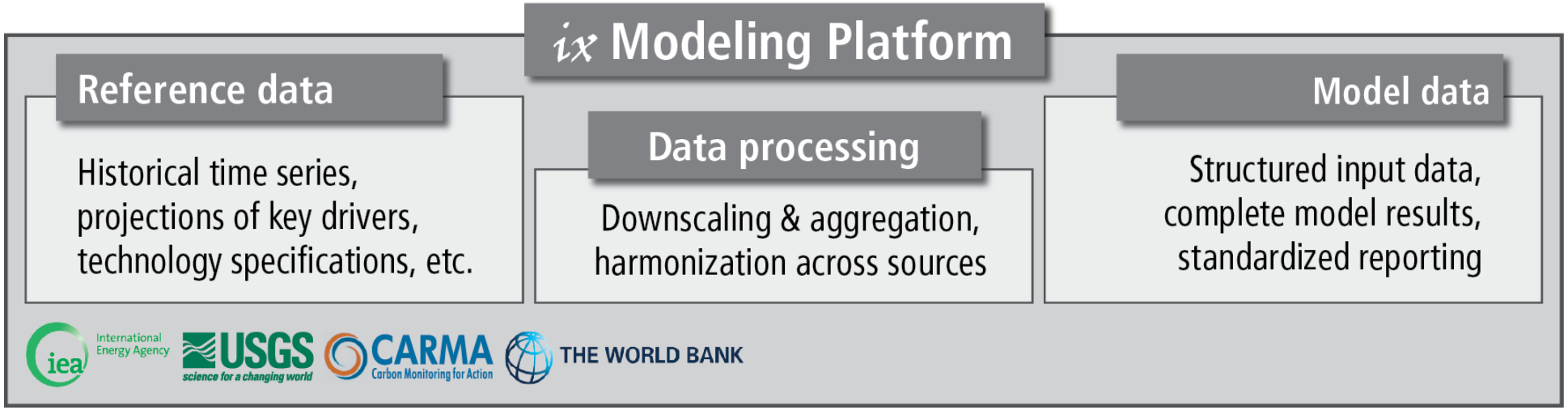
- integration of models & scientific analysis between different disciplines
- across **spatial and temporal** levels of disaggregation
- highest level of transparency and scientific reproducibility for a wide audience



Key features of the *ix* modeling platform

The MESSAGE$_{ix}$ framework: 1. Data management

A central data management system (ixmp)



Good data management is crucial for modeling & scientific analysis:

… version-controlled and traceable input data for model development

… reference data for calibration and verification

… efficient workflows based on standardized data processing tools and a common data interface

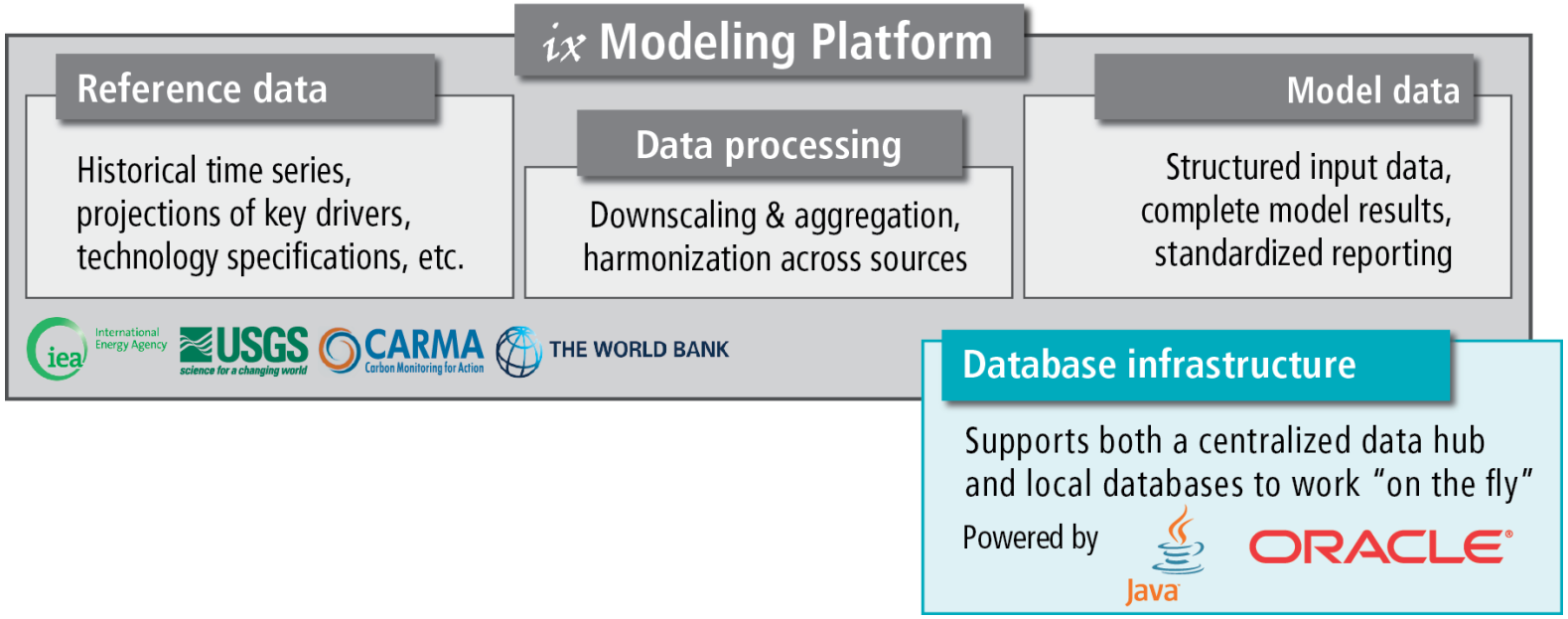
The MESSAGE$_{ix}$ framework: 2. Database backend

Supported by a high-performance database architecture

The platform...

… 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"

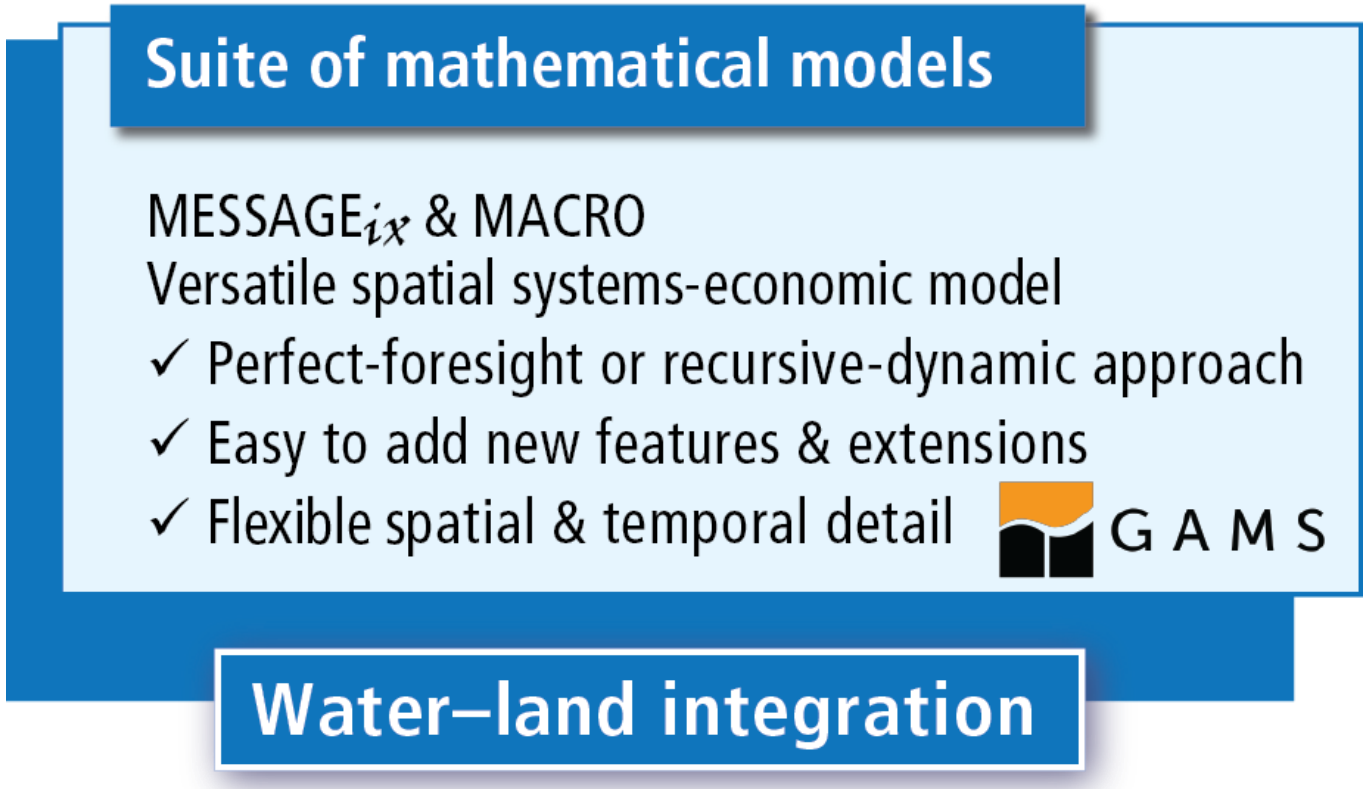


The MESSAGE$_{ix}$ framework: 3. Integration with GAMS

Connected to high-performance numerical programming

The platform has an interface to GAMS, a versatile software for mathematical programming & optimization.

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



The MESSAGE$_{ix}$ framework: Documentation

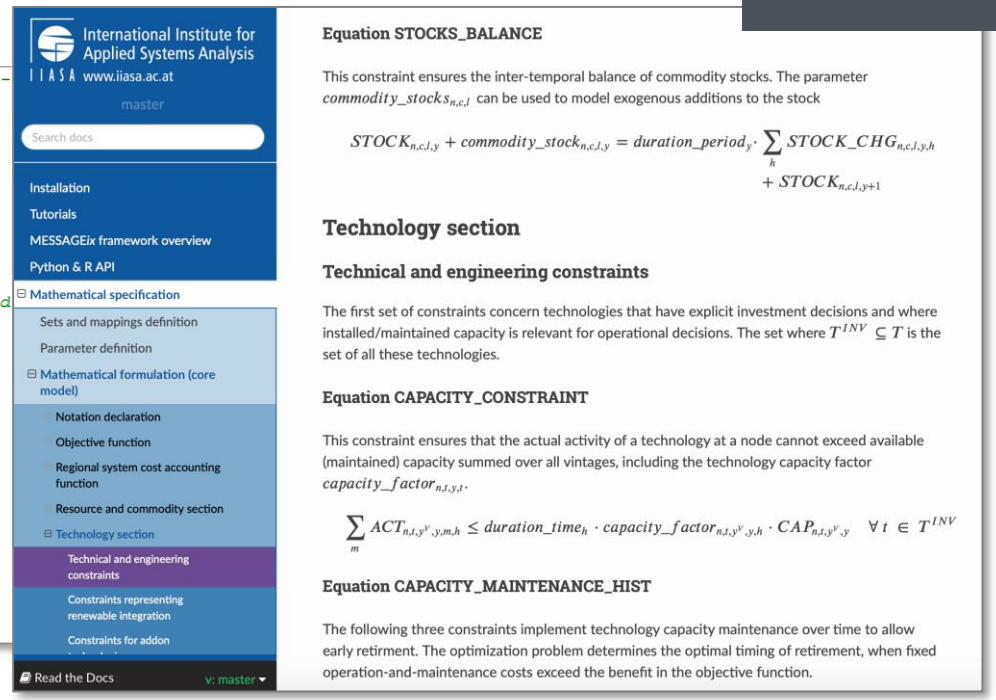
Implementing tools for comprehensive documentation

The framework ensures transparency and intelligibility
through “auto-documentation” of all codes & packages on readthedocs.org

⇒ Documentation of all scientific programming packages using ‘sphinx‘

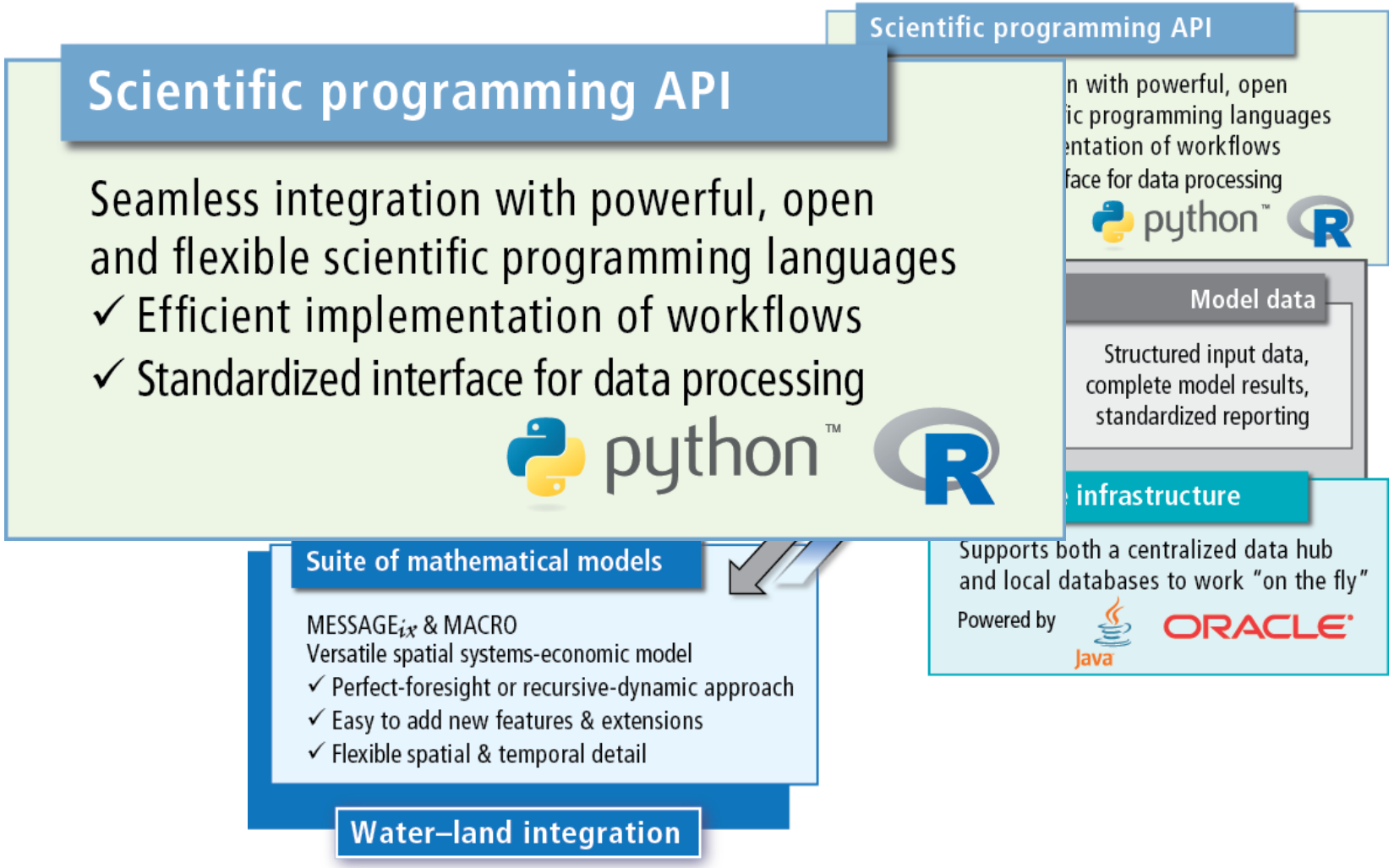
⇒ Documentation of the mathematical equations generated automatically from LaTeX mark-up in the GAMS code

```
*---------------------------------------------------------------------------
***
* 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) ;
```



The MESSAGE$_{ix}$ framework : 4. Scientific programming

Interfaces to scientific programming for advanced users



The MESSAGEix framework: 5. Collaborative research

Geared towards best-practice in collaborative research

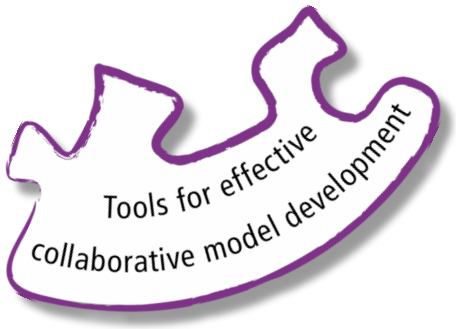
The platform facilitates collaborative model development

… through comprehensive version control of data, model codes and scripts

… implementing "continuous integration"

⇒ automated unit-testing of new features to ensure stable code base

https://github.com/iiasa/message_ix



- Google Group (questions and answers):
  https://groups.google.com/forum/#!forum/message_ix

The MESSAGE$_{ix}$ framework: 6. Interactive web user interface

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

Web-based user interface

Features

- ✓ Visualization of input data & model results
- ✓ Intuitive drag & drop tables and graphs
- ✓ Data import & export using MS Excel

Powered by HTML CSS JS

The MESSAGE$_{ix}$ framework

Facilitating transparency and reproducibility of research

Web-based user interface

Features
- ✓ Visualization of input data & model results
- ✓ Intuitive drag & drop tables and graphs
- ✓ Data import & export using MS Excel

Powered by HTML CSS JS

Scientific programming API

Seamless integration with powerful, open and flexible scientific programming languages
- ✓ Efficient implementation of workflows
- ✓ Standardized interface for data processing

python R

ix Modeling Platform

Reference data

Historical time series, projections of key drivers, technology specifications, etc.

Data processing

Downscaling & aggregation, harmonization across sources

Model data

Structured input data, complete model results, standardized reporting

iea International Energy Agency · USGS science for a changing world · CARMA Carbon Monitoring for Action · THE WORLD BANK

Database infrastructure

Supports both a centralized data hub and local databases to work "on the fly"

Powered by Java ORACLE

Suite of mathematical models

MESSAGE$_{ix}$ & MACRO
Versatile spatial systems-economic model
- ✓ Perfect-foresight or recursive-dynamic approach
- ✓ Easy to add new features & extensions
- ✓ Flexible spatial & temporal detail

GAMS

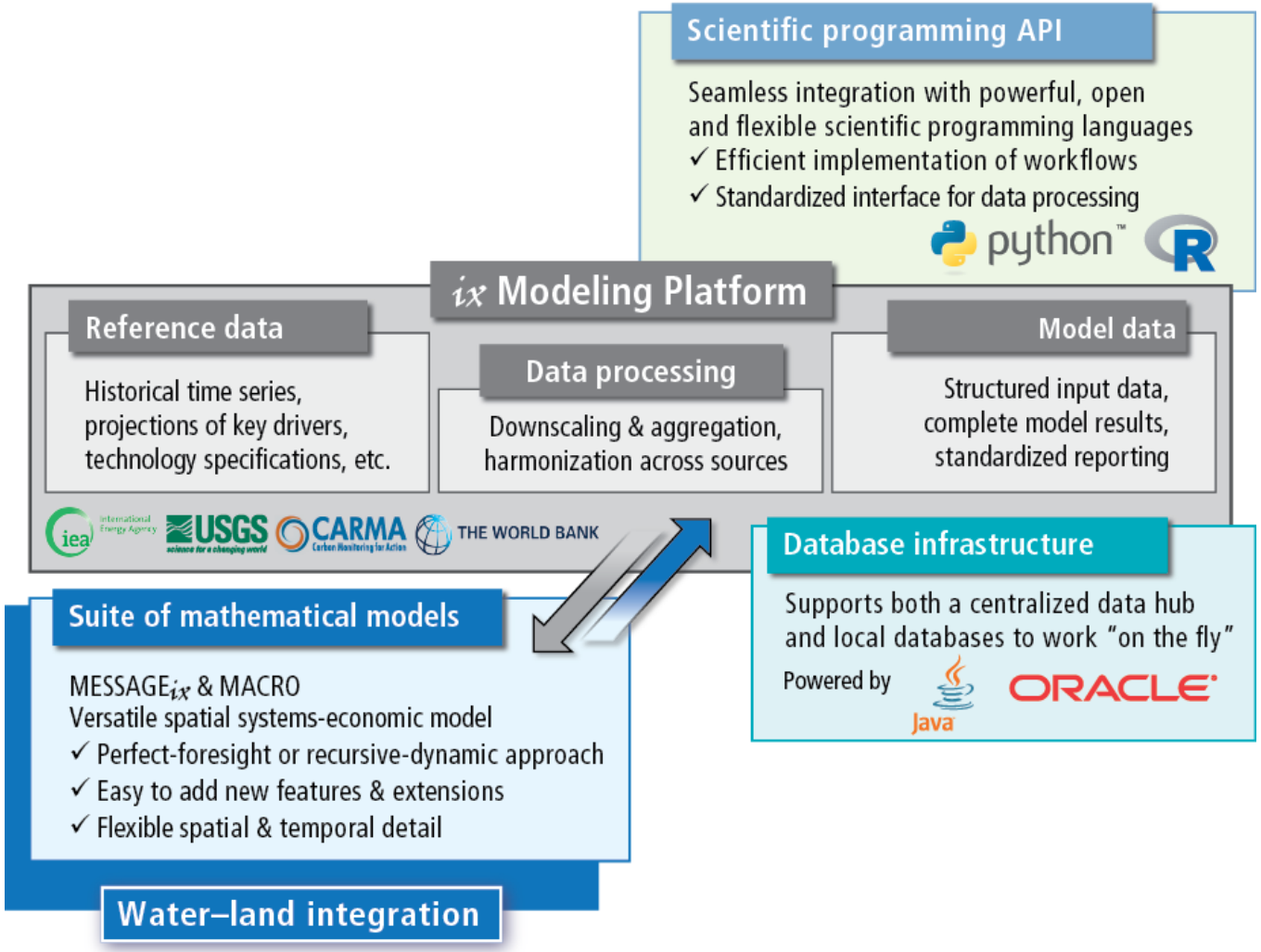
Water–land integration

All model codes & workflow scripts are under version control for efficient collaboration

GitHub

The MESSAGE$_{ix}$ framework : Workflow of modeling

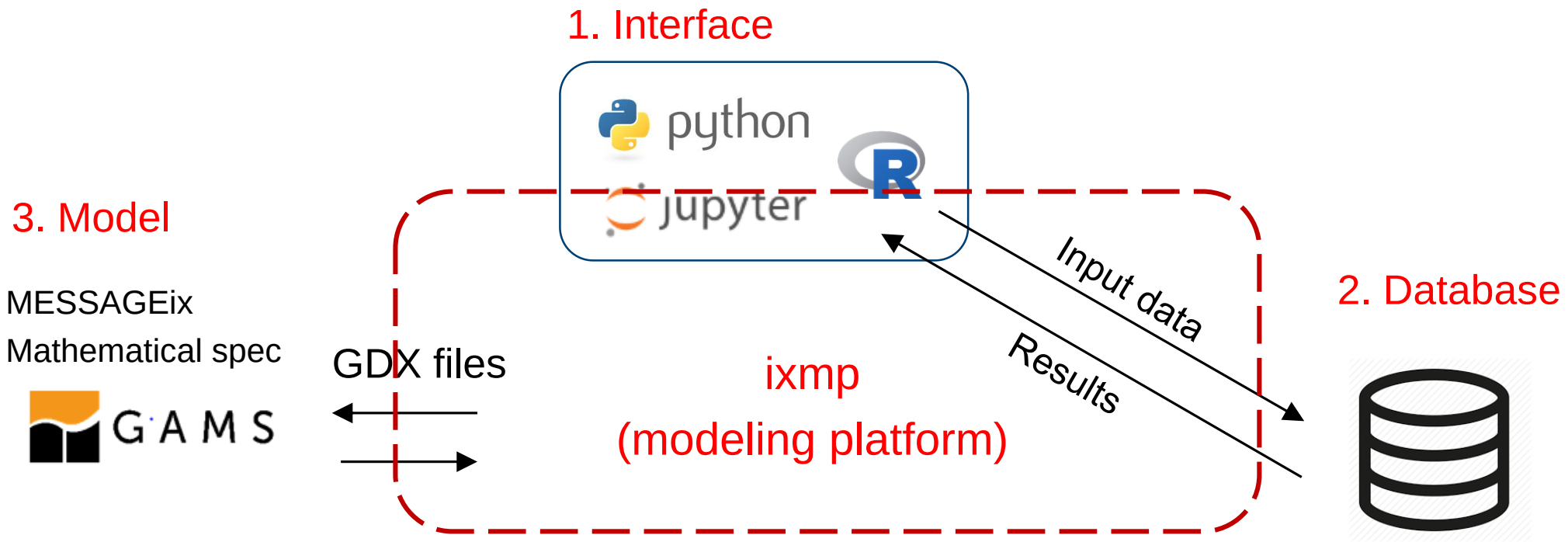
Flexible and high performance processes



The MESSAGE$_{ix}$ framework : 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)
- To see model data and results: load from database, model GDX files, etc.

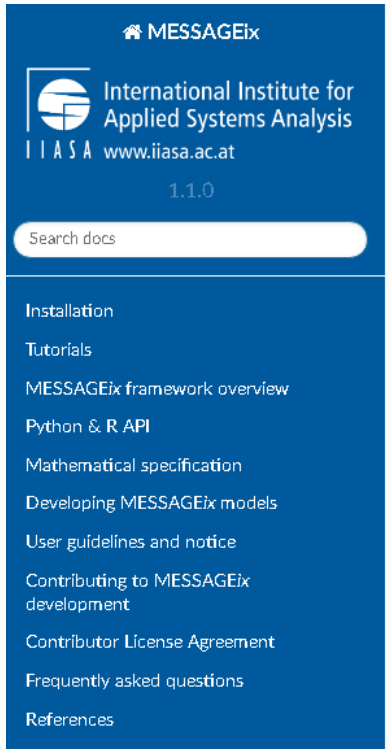


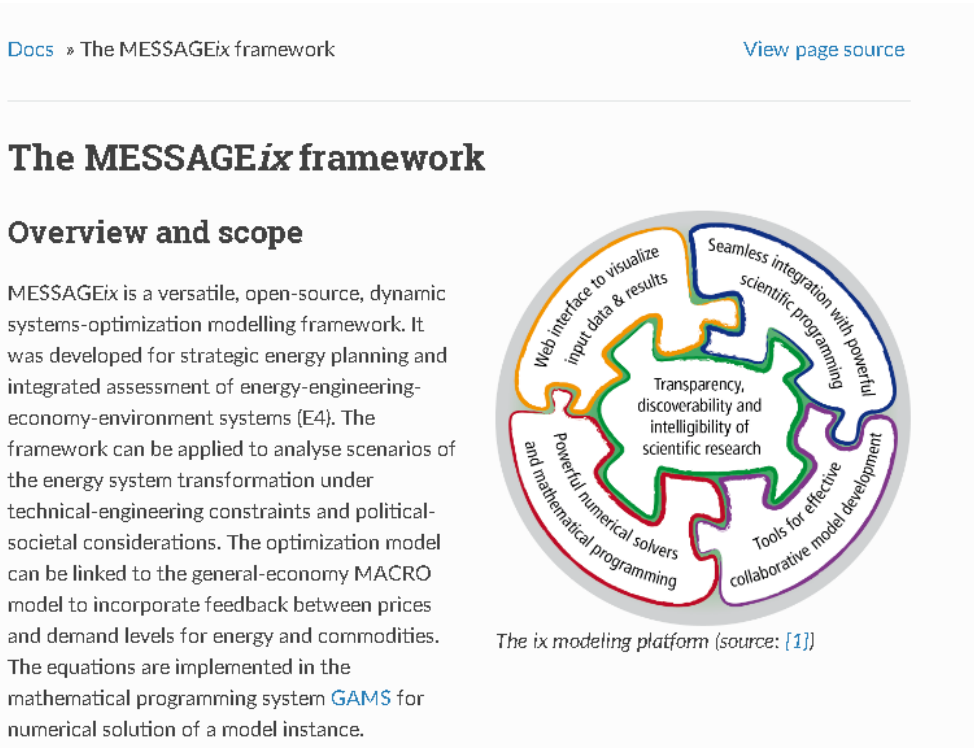
MESSAGEix Website: main source of information

- Main page:
  ⇒ https://MESSAGE.iiasa.ac.at

- Open-source GitHub repository:
  ⇒ https://github.com/iiasa/message_ix
  (contribution guide)

- Tutorials and examples





The MESSAGEix framework: Installation

Two types of installation

1. Install MESSAGEix through Anaconda

- You only want to use the public release (latest version)
- You don't aim to contribute to the code on Github
- You will be still able to develop your features to your code

2. Install through the source (advanced users, developers)

- You want to test and review the latest features (i.e., the ones after the latest public release)
- You want to contribute to the code
- You know about the collaborative code development

The MESSAGEix framework: Installation (2)

A checklist

1. Install the required software

- Anaconda (set as PATH environment variable)
- GAMS (set as PATH environment variable)

2. Install MESSAGEix

- Open Anaconda Prompt window, and type:

```
$conda install -c conda-forge message-ix
```

3. Download Tutorials (examples for learning the model)

- In Anaconda Prompt window type:

```
$messageix-dl --local_path "C:\Users\yourname\myfiles\MESSAGEix"
```

(In case of path permission or access error, still Tutorials might have been downloaded)

The MESSAGEix framework: After installation

What is where?

1. ixmp and message_ix python packages

- Locate your Anaconda (python) library and navigate to *site-packages*
  - You can open windows command line and type:

    `$where Anaconda`

  - Then, navigate to *site-packages* (C:\...\Anaconda3\Lib\site-packages)
- You should be able to see two packages *ixmp* and *message_ix*

2. Mathematical model folder

- Model folder is by default under messgae_ix folder
- Model folder can be changed to a new folder (optional)

  Open Conda command window, and type:

  `$messageix-config --model_path /path/to/model`

The MESSAGEix framework: Mathematical formulation

Everything is at your disposal!

1. Looking into the GAMS files
    - Locate your “model” folder (for example, C:\...\message_ix\message_ix\model)
    - Create a GAMS project there (optional)
    - MESSAGE formulation in (C:\...\model\MESSAGE): for example look at `model_core.gms`
    - Input data in (C:\...\model\data): GDX files
    - Output results in (C:\...\model\output): GDX files

Linear programming (LP) (reminder)

Applications of LP

- Production management
- Personnel management
- Marketing management
- Resource/ inventory management
- Blending problem, etc

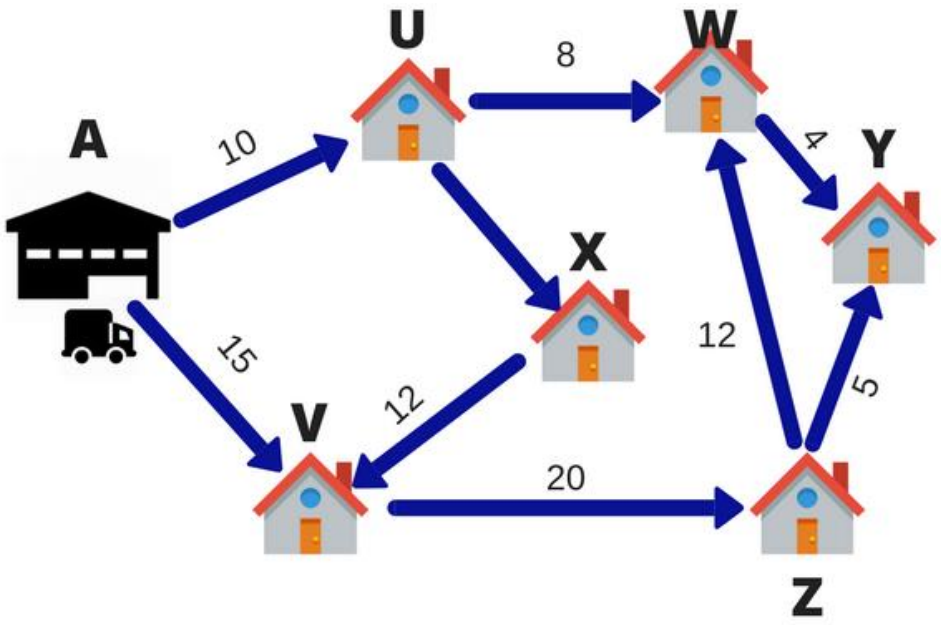


image: deepai.org

Principle:

Maximizing the utility (use of resources)

Or Minimizing the cost of meeting a service ➔ MESSAGEix

MESSAGEix: a linear optimization model

Minimizing cost of the system

- **Objective:** The least cost option for meeting certain services (demand)
- **System:** a set of technologies (processes), resources, and products
- **Cost of the system**: installing/maintaining ***capacity***, cost of ***activity*** (operation), and emissions, land use and relation costs (if any)
- Constraints: maximum use of a technology, growth/decline rates of activity, capacity factor, etc.

A note on "capacity" and "activity" (MESSAGEix formulation)

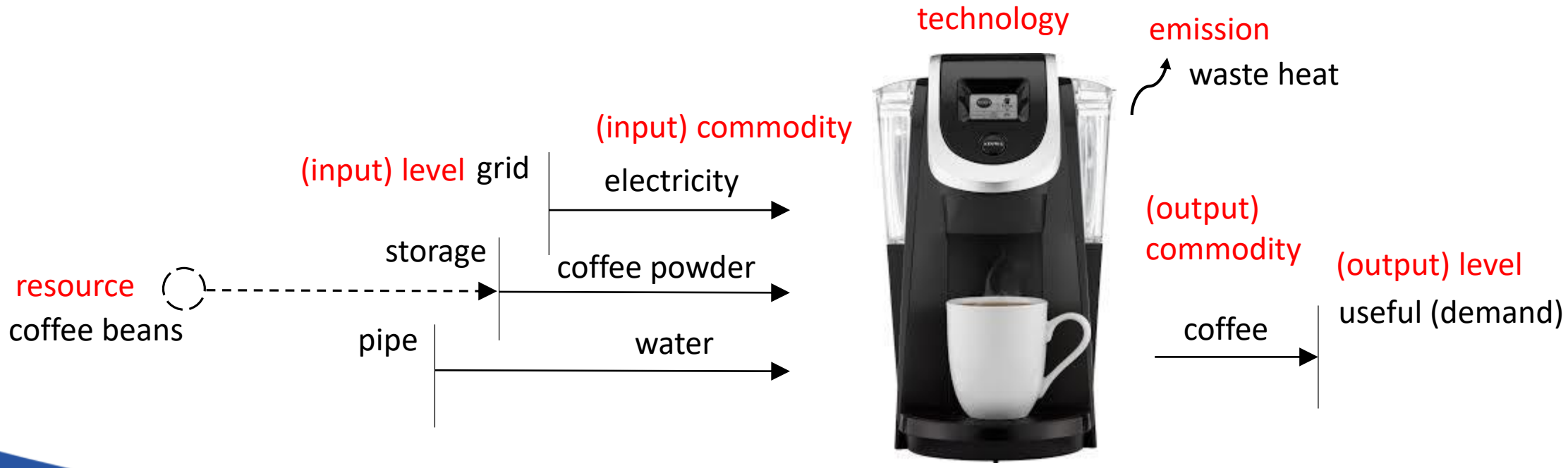
- **Capacity:** installed units of a technology (e.g. three cars)
- **Activity:** operation of that technology (e.g., 3 h usage of each car per day)
- **Reminder:** capacity ≠ activity

MESSAGEix: a technology-based model

Technologies and resources meet demand

- Example **technologies:** electric car, reactor, pipeline, power plant, building, ship, industrial process

A sample technology: coffee machine



MESSAGEix: Sets and Parameters

Sets:

- List of elements for building a model
- Example: technology, commodity, level, node, etc.

CONSTRUCTION MATERIALS		
Part	**Cast Iron Pump**	**Stainless Steel Pump**
Inlet / Motor Bracket	Cast Iron	Cast 316 SS
Discharge Housing	Steel	316 SS
Pump Housing	304 SS Tubing	316 SS Tubing
Impellers	Noryl	Noryl
Diffusers	Noryl	Noryl
Wear Rings	316 SS	316 SS
Shaft & Coupling	316 SS / 416 SS	316 SS
Shaft Bearing Sleeve	316 SS	316 SS
Shaft Bearing	Bronze	Rulon
Mechanical Seal	Carbon/Ceramic	Carbon/Ceramic
	302 SS, Buna N	316 SS, Viton
Mechanical Seal Spacer	416 SS	316 SS
O-Rings	Buna-N	Viton

Parameters:

- Adding information about sets
- Defining quantities (specification)
- Relating sets to each other, etc.

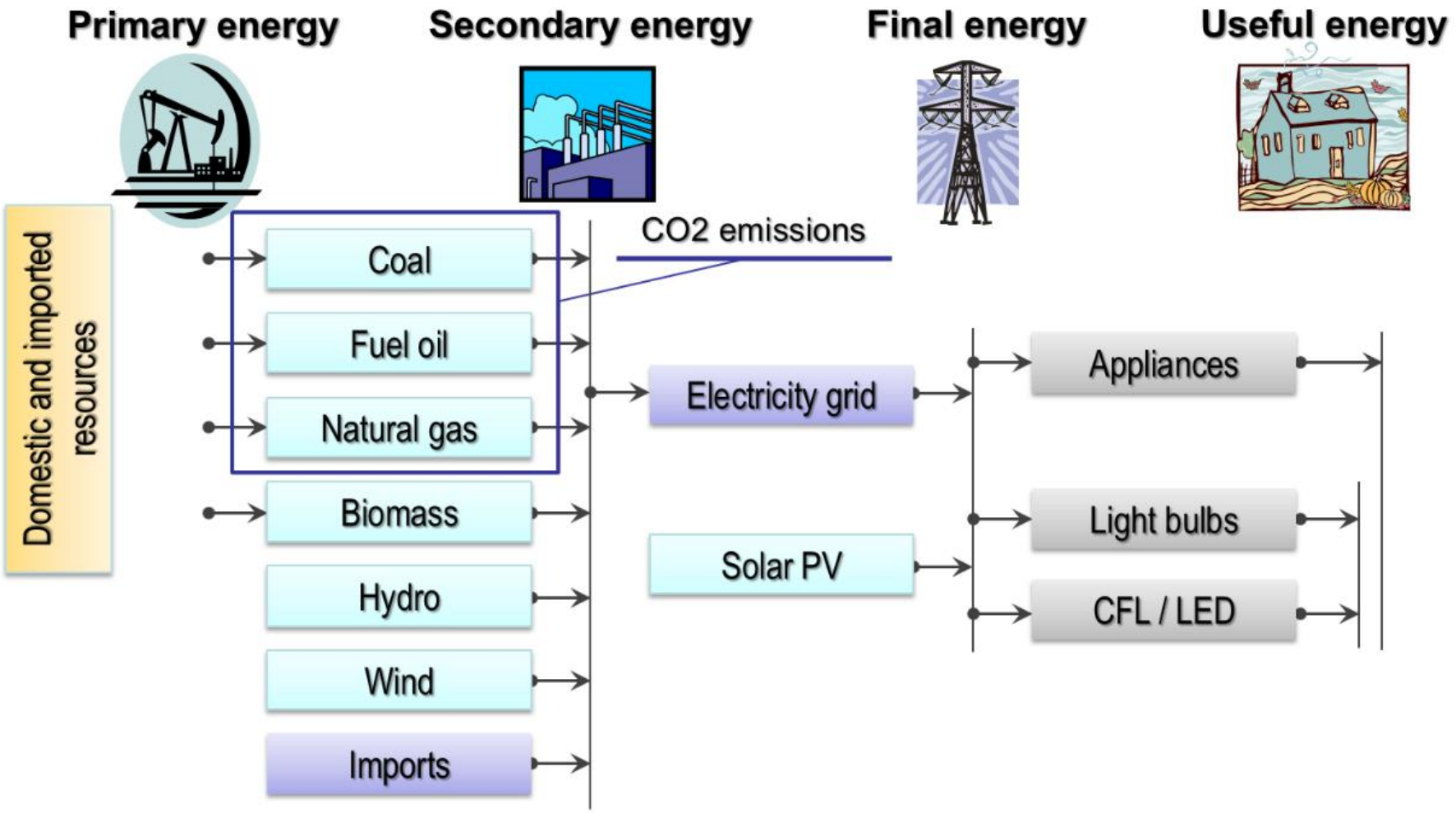
Equations:

- Relationship between sets, parameters, **variables**, etc.
- Building the model

Images from: http://hewa.com/wp-content/uploads/2016/12/0material.jpg and https://weburbanist.com/wp-content/uploads/2015/11/arc-kit-2.jpg

MESSAGEix: Energy system

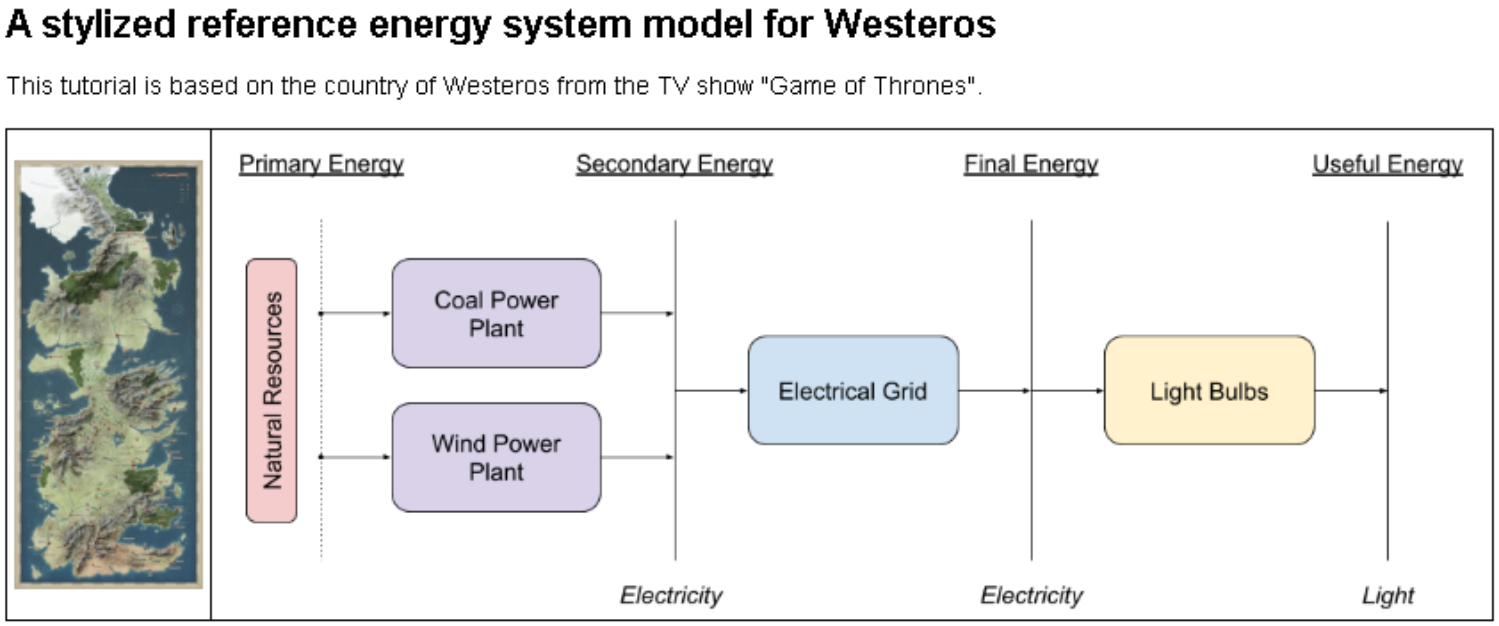
Technologies, commodities, levels, etc

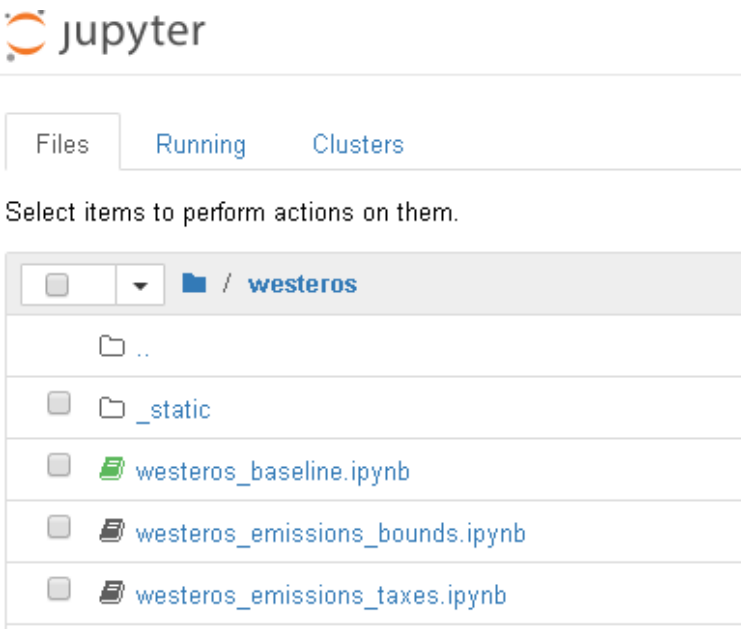


Working with tutorials

Building an energy system from scratch

- Locate your tutorial folder in your machine
- Then, open a command window and call ***jupyter notebook***
- Navigate to the folder for Westeros tutorials and open the baseline





Westeros baseline

Different steps of modeling

- Creating a new scenario (or loading an existing one)
- Declaring required sets (*node, technology, commodity, level*, etc.)
- Defining required parameters (adding numeric data, relating sets to each other, etc.)

  - demand

  - techno-economic parameters

  - bounds and dynamic constraints
- Solving the model
- Postprocessing and plotting

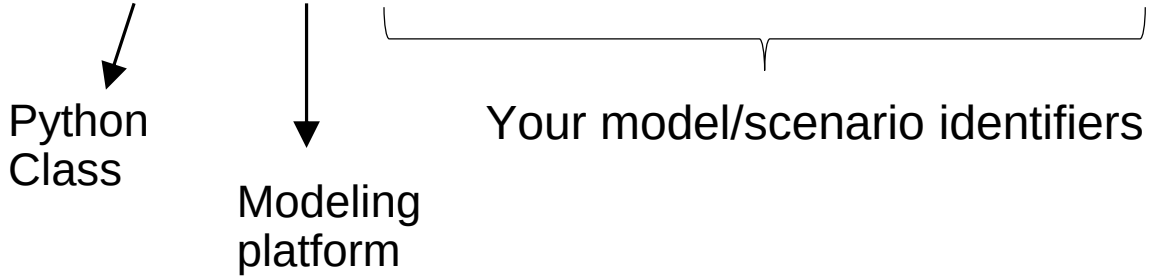
Working with MESSAGEix scenarios

A short note on model/scenarios

- Loading the ixmp platform (connection to the database):

```
mp = ixmp.Platform(dbtype='HSQLDB')
```

- Creating a new scenario:
- `my_scen = message_ix.Scenario(mp, model, scenario, version='new')`



Example: `model = 'building energy system', scenario = 'baseline' (or 'low efficiency')`

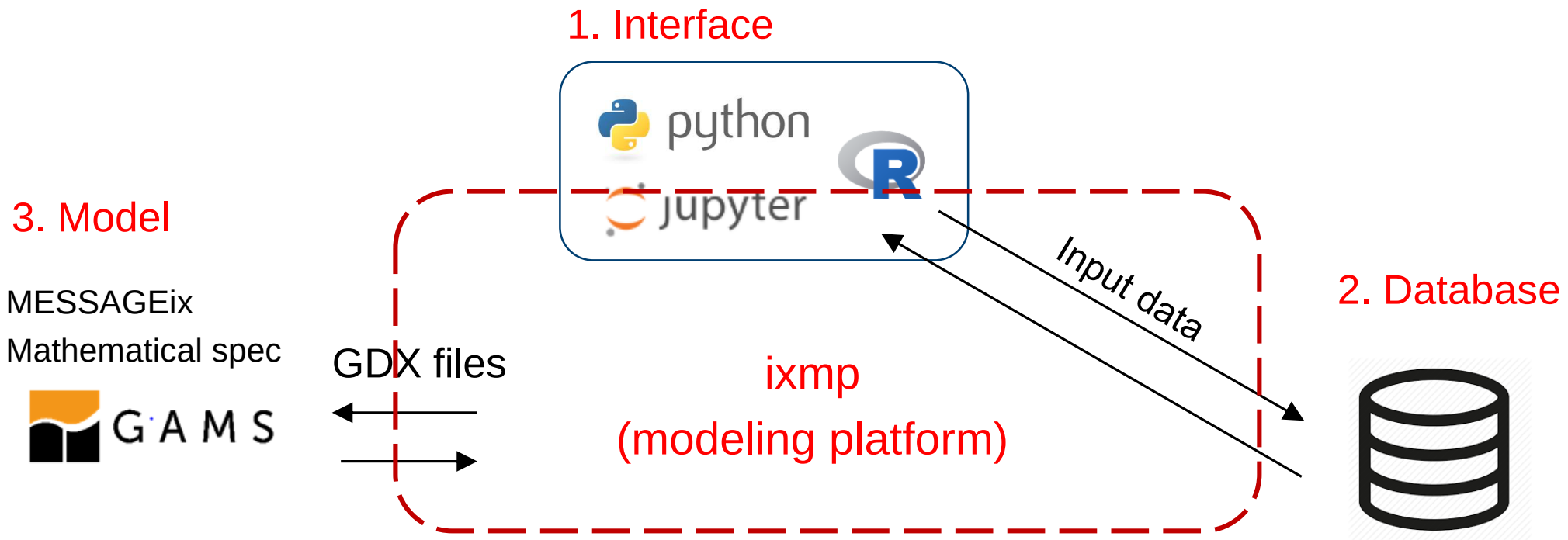
- Loading an existing scenario:

```
my_scen = message_ix.Scenario(mp, model, scenario, version=1)
my_scen = message_ix.Scenario(mp, model, scenario)
```

The MESSAGE$_{ix}$ framework : Workflow of modeling

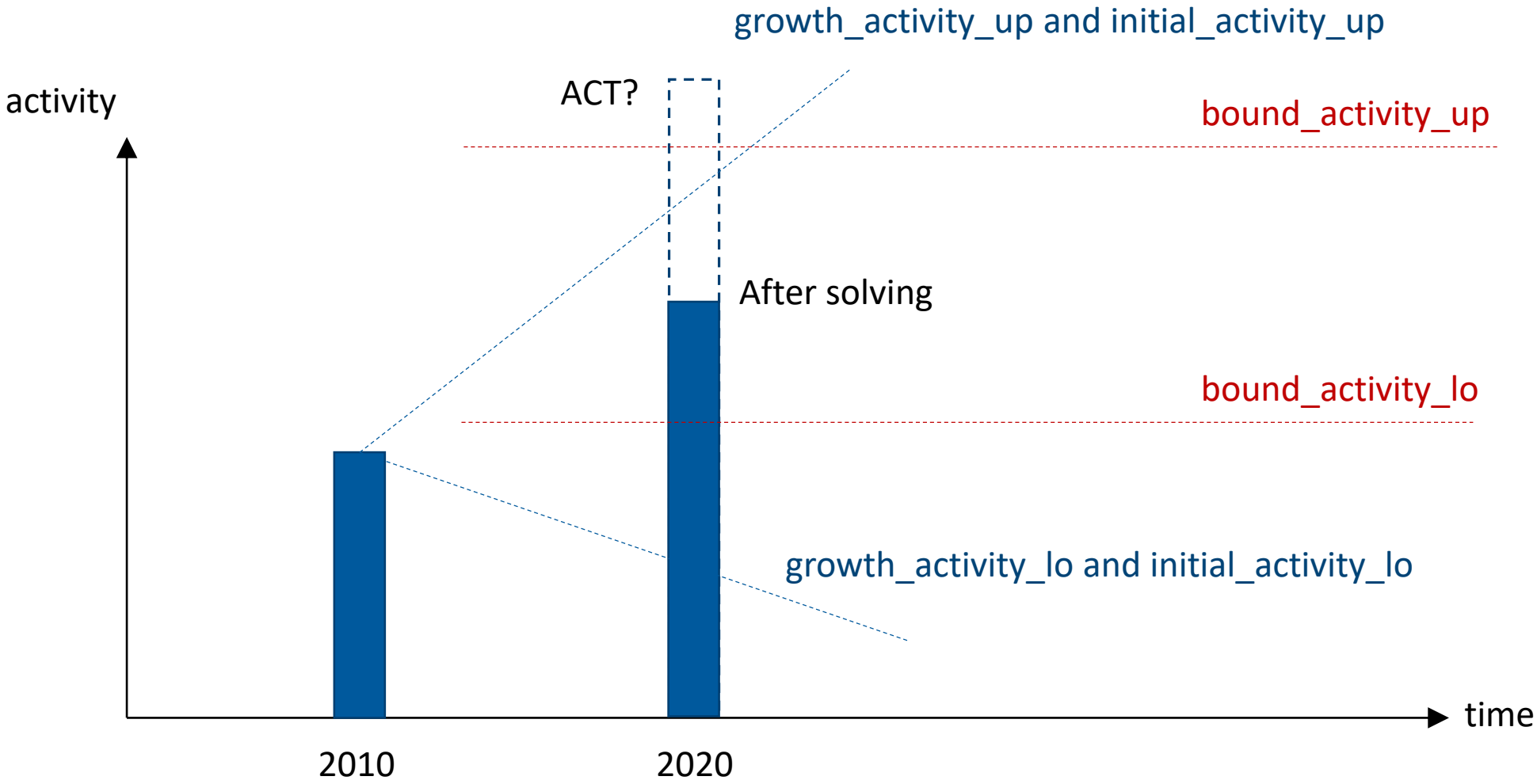
Reminder

- 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.



Dynamic constraints

Controlling behavior of technologies over time



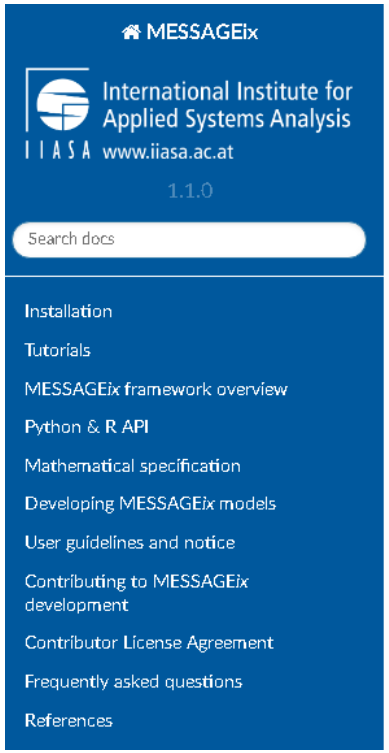
Link to the documentation

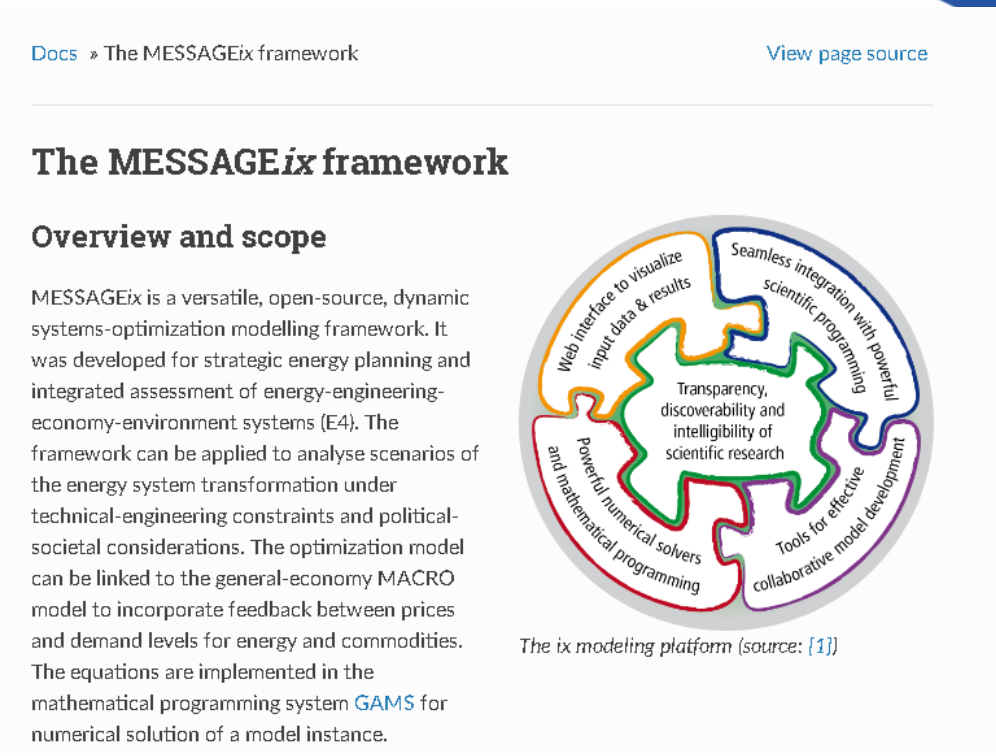
More information

- Main page:
  ⇒ https://MESSAGEix.iiasa.ac.at

- Open-source GitHub repository:
  ⇒ https://github.com/iiasa/message_ix
  (contribution guide)

- Tutorials and examples





- Scientific reference to the MESSAGE*ix* framework:

  Huppmann et al. (2019). *The MESSAGEix Integrated Assessment Model and the ix modeling platform: An open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development.* Environmental Modelling & Software 112: 143-156. DOI: 10.1016/j.envsoft.2018.11.012

Thank you very much for your attention!

Volker Krey
Deputy Program Director – Energy Program
International Institute for Applied Systems Analysis (IIASA)
Laxenburg, Austria
krey@iiasa.ac.at
www.iiasa.ac.at