The MESSAGE$_{ix}$ modeling framework for $i$ntegrated and x-cutting analysis

7-10 Sep 2020

Energy Program, International Institute for Applied Systems Analysis (IIASA), Austria

The MESSAGE$_{ix}$ workshop team, Sep 2020

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Agenda for the week

- **Day 1**: Introduction to the MESSAGE$_{ix}$ framework
  - ⇒ Discuss practice of modeling & model development.
  - ⇒ Learn terminology: model, framework, platform, etc.
  - ⇒ Understand the different components of MESSAGEix and their capabilities.
  - ⇒ Resolving issues of installation (if needed).

- **Days 2**: MESSAGE$_{ix}$ as an optimization model
- Describing the main objective of the mathematical model
- A technology-based, bottom-up modeling logic
- Use of basic model framework capabilities, using a rudimentary example.

MESSAGE$_{ix}$ modeling workshop (2)

Agenda for the week

- Day 3: Energy modeling using MESSAGE$_{ix}$
  - ⇒ Main modelling parameters and input data of a MESSAGEix model
  - ⇒ Walk through some simple, complete energy models from the MESSAGE$_{ix}$ tutorials.
  - ⇒ Adding energy policy constraints to a MESSAGEix model

- Day 4:
  - ⇒ Post-processing or “reporting”: calculations based on model outputs.
  - ⇒ Good research, modeling, and software development practices.
  - ⇒ Continous integration

Today's agenda

- Examples of MESSAGE$_{ix}$ applications.
- Breakout discussion: modeling and model development.
- Detailed tour of the MESSAGE$_{ix}$ "ecosystem" of tools, including terminology.
- Installing the software (preparation for Sessions 2–4).

<u>Ground rules</u>

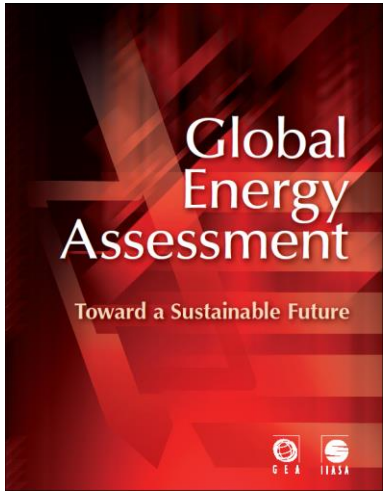
- Questions are welcome and valid.
  - ⇒ Raise your hand (using Zoom features).
  - ⇒ Ask in chat: "Everyone", or to a colleague with " (IIASA)" in their name.
  - ⇒ Follow-up via e-mail.
- Respect for diversity of participants, their level of knowledge, and their time.

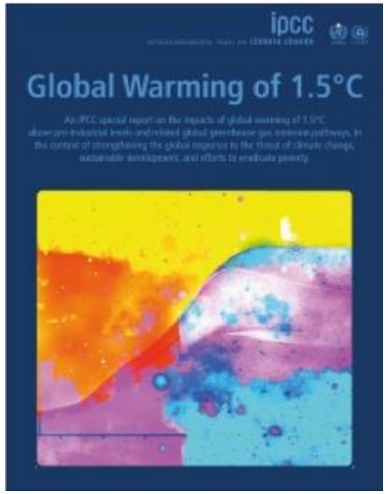
The MESSAGE model at IIASA

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

- Since 1980s used for assessing sustainable development and energy/climate policies at national, regional and global scales.
- MESSAGE: a systems engineering, long-term planning optimization model.
- MESSAGE widely in use in other organizations like IAEA and member countries.
- In 2018, transformed to an open-source modelling framework: **MESSAGEix**
- Relying on the state-of-the-art and powerful data management infrastructure
- Building a community of developers, transparency and knowledge sharing

- Sample 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)

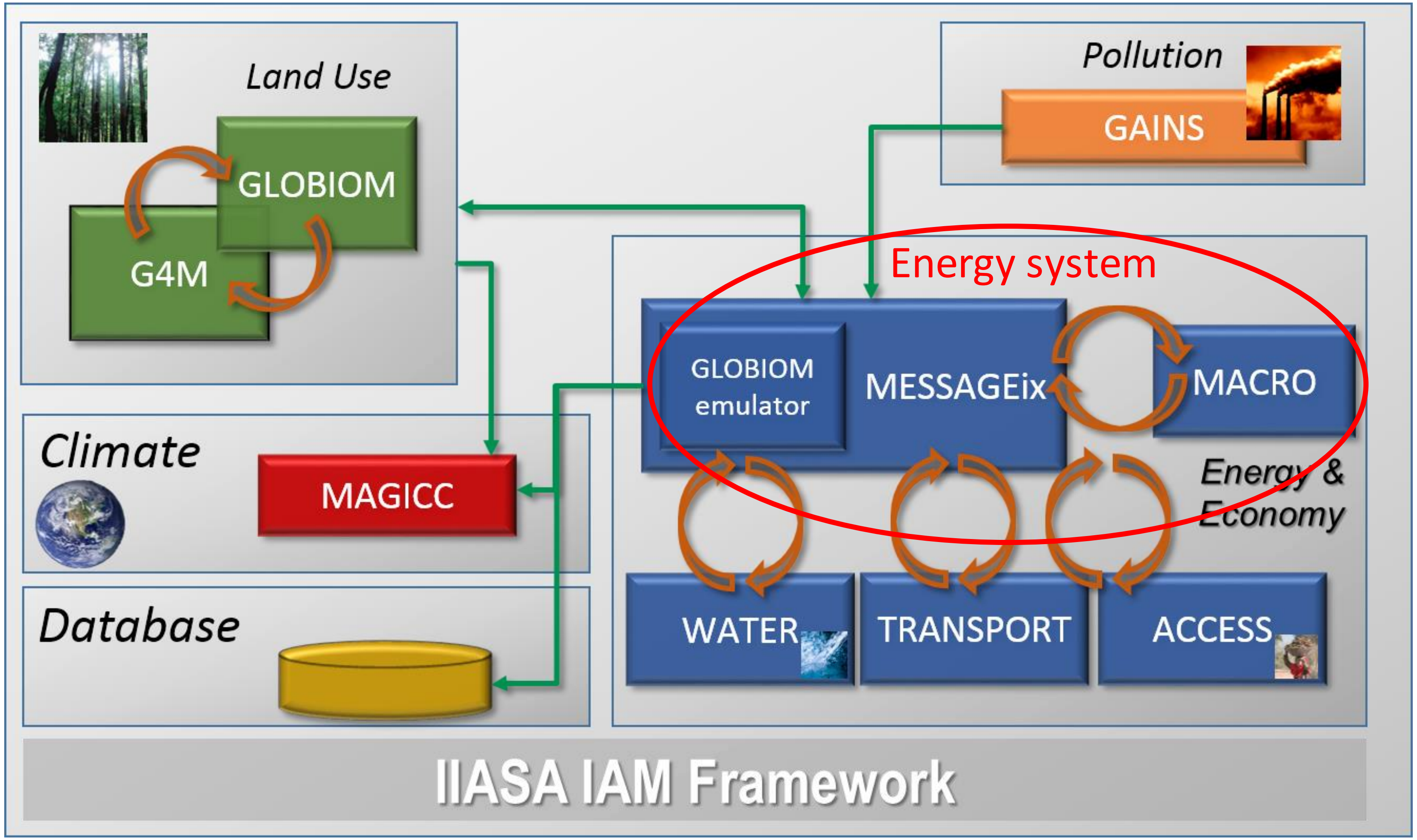




http://www.ipcc.ch/report/sr15/)

IIASA's Integrated Assessment Model (IAM)

MESSAGE$_{ix}$ as an energy system model is at the core



MESSAGE$_{ix}$ example projects 1: Global Electricity Interconnector

What is the impact on renewbel energy integration?

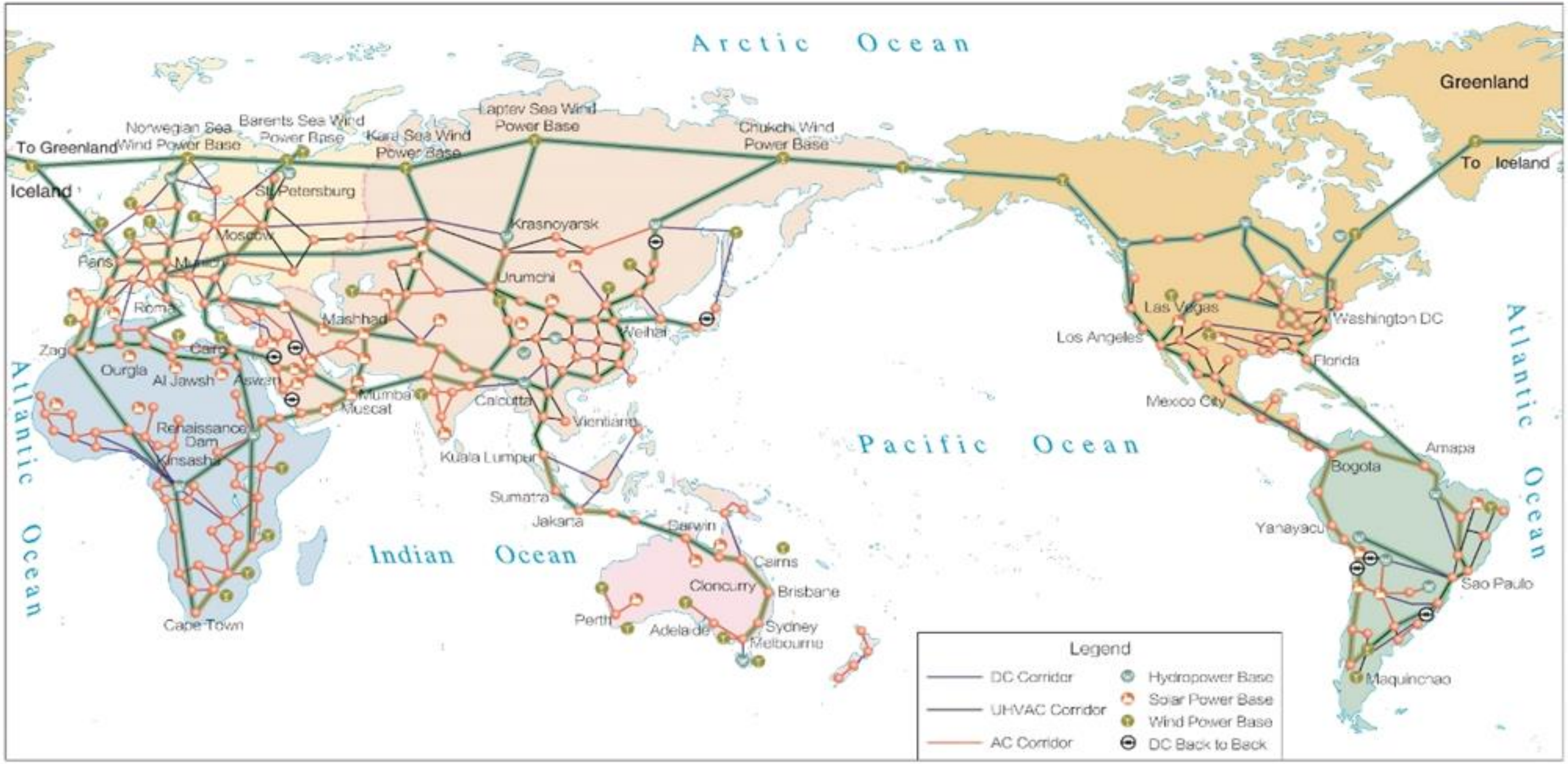


Image: GEIDCO

MESSAGE$_{ix}$ example projects 2: Regional energy transition

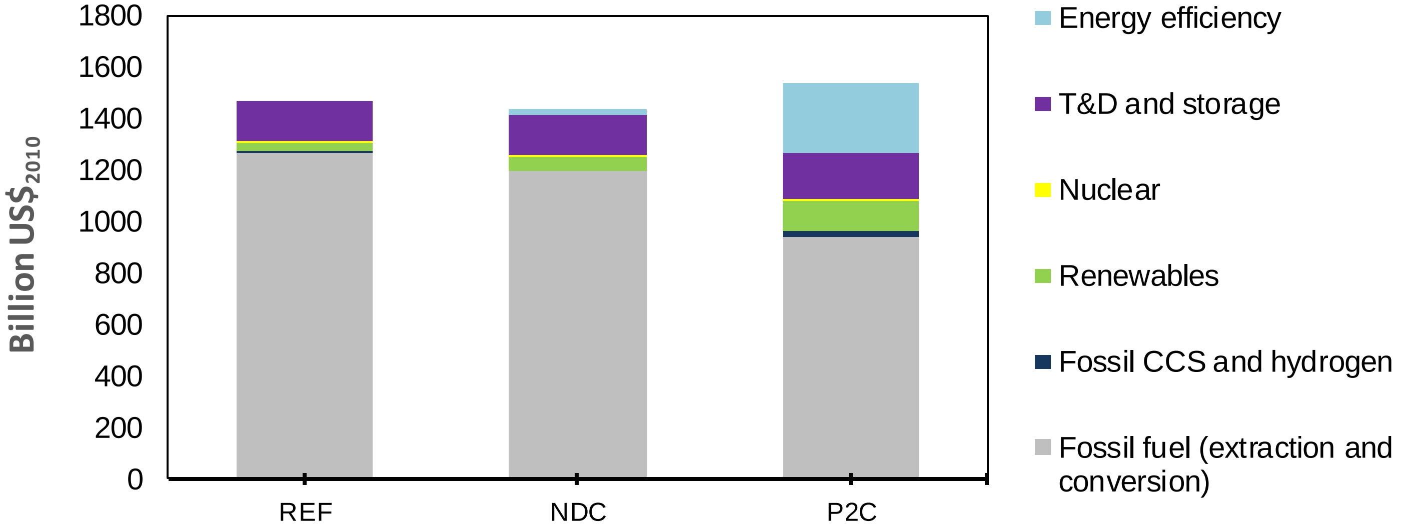
Central Asia: conflict between energy and water demand

Modelling of hydropower storage solutions and sub-annual timeslices

- Impact of gas demand in China on gas exports from the region
- Coal and gas demand in a 2-degree world
- Role of renewables in the region
- Assessment of investment needs

image: moneyw eek.com

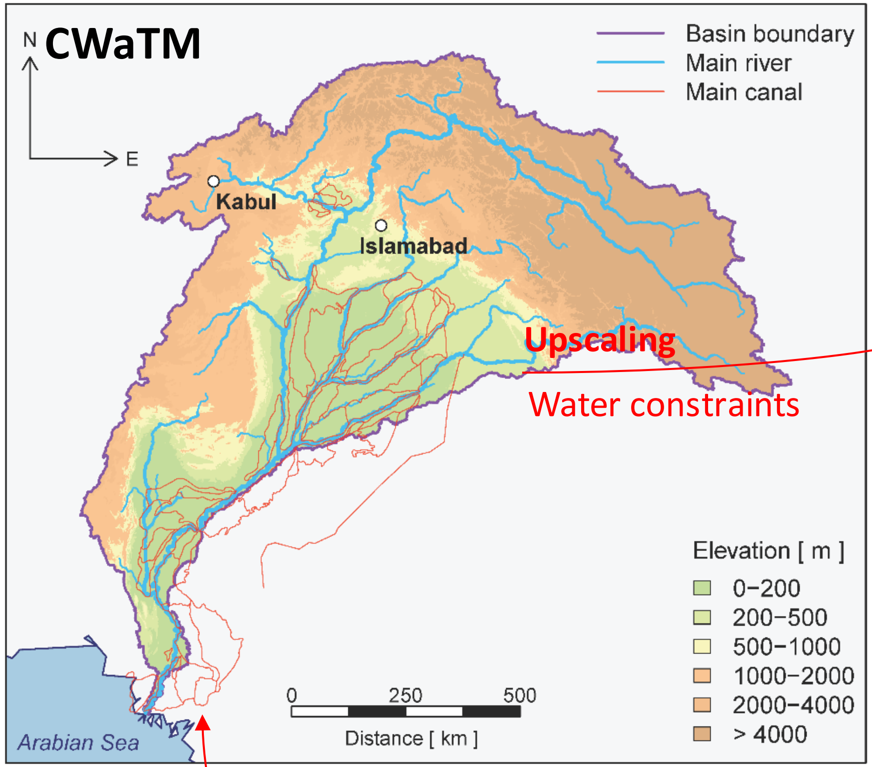
Investment needs in Central Asia (2020-2050)

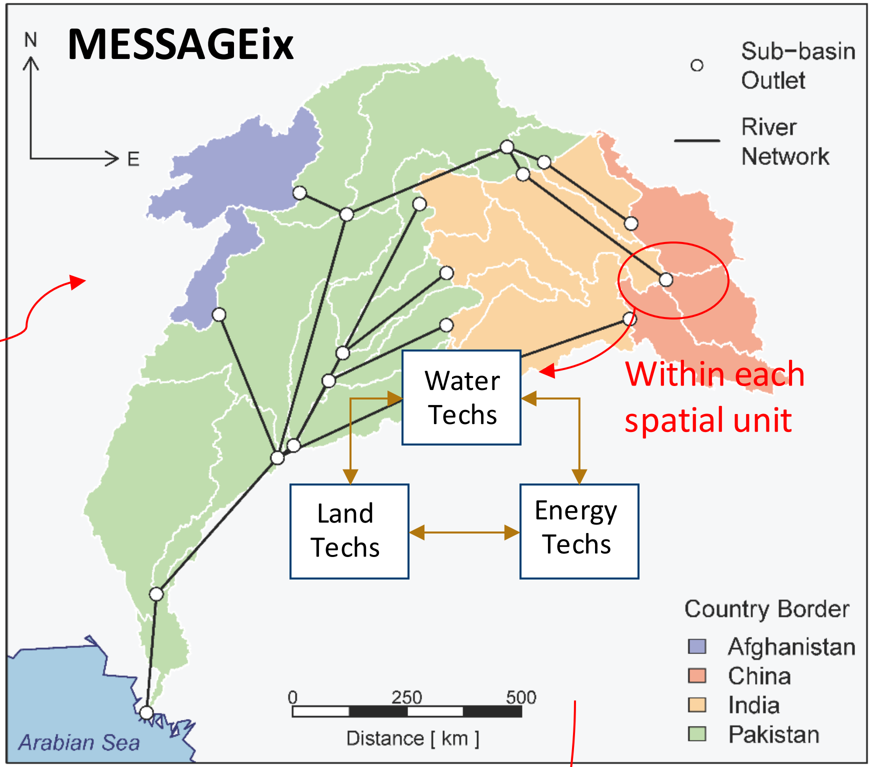


REF: reference scenario, NDC: nationally determined contributions, P2C: 2-degree

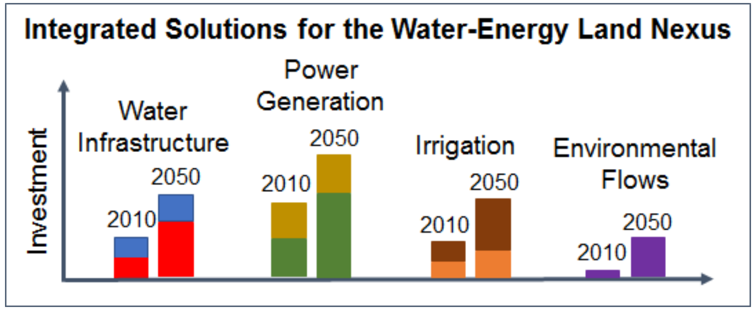
MESSAGE$_{ix}$ example projects 3: NEST model framework

Transboundary analysis of water-energy-land use (Indus Basin)





Downscaling
Water and land-use



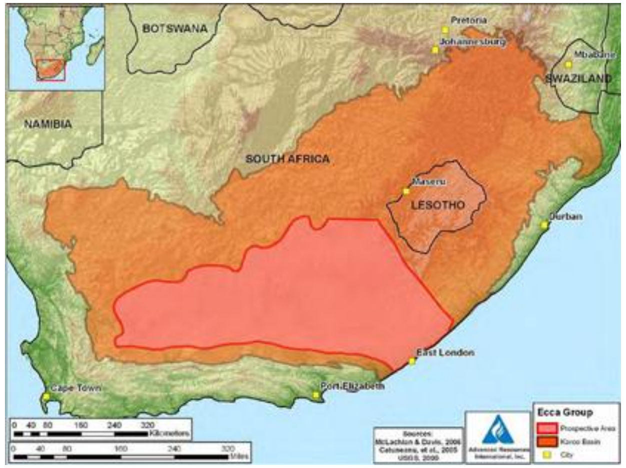
Minimize total system cost

Vinca et al., (forthcoming)

MESSAGE$_{ix}$ example projects 4: South Africa (MESSAGE-ZA)

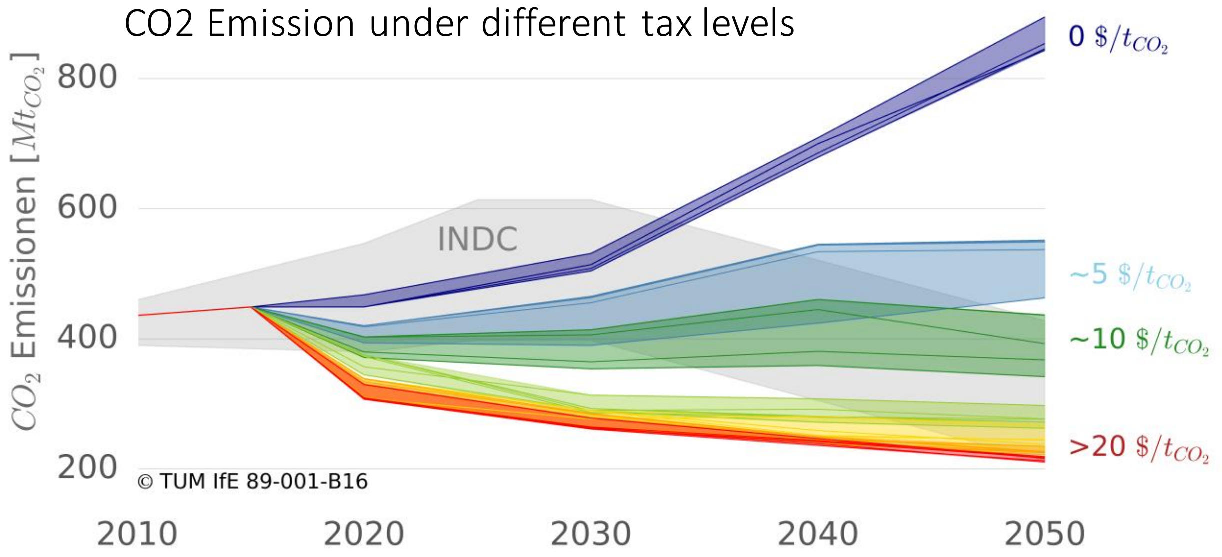
Shale gas in South Africa

- South Africa beyond shale gas to meet NDC pledges
- Gas can function as a transition fuel from a coal to renewables
- Methane emissions from shale gas production need to be managed to avoid climate effects of gas usage
- Water scarcity might be an obstacle to shale gas use



Source: EIA - World Shale Gas Resources (April 2011)

Orthofer, C., Huppmann, D. and Krey, V., 2019.
South Africa After Paris—Fracking Its Way to the NDCs?.
Frontiers in Energy Research, 7, pp.art-20.

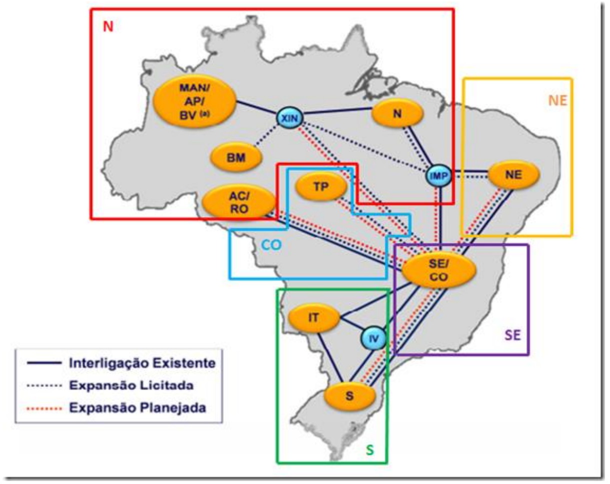


MESSAGE$_{ix}$ example projects: others

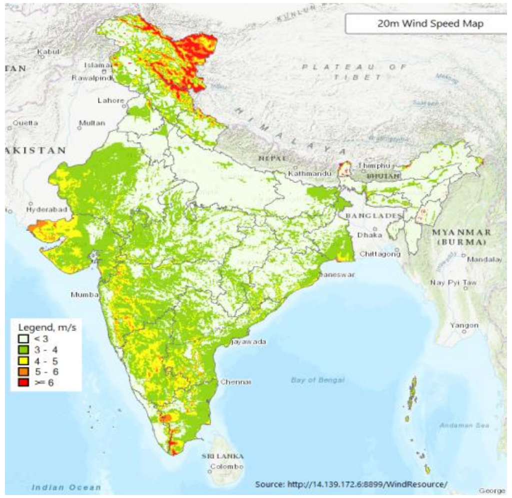
National Policies and International Agreements

- Role of Brazilian Amazon on country’s NDC
- Energy demand in India and vulnerability assessment
- Co-developing water-energy-land modeling tools with the Indian government
- Role of gas exploration in energy security of Israel

COPPE UFRJ
Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia



Niti Aayog
नीति आयोग
National Institution for Transforming India



Ministry of Energy
www.energy.gov.il

The remainder of today's session

What to expect?

- Learn about capabilities and organization of the MESSAGE$_{ix}$ framework.
- Learn about the installation and location of the installed packages.
- Be able to find the relevant source for more information about the framework.

Requirements for working on MESSAGE$_{ix}$

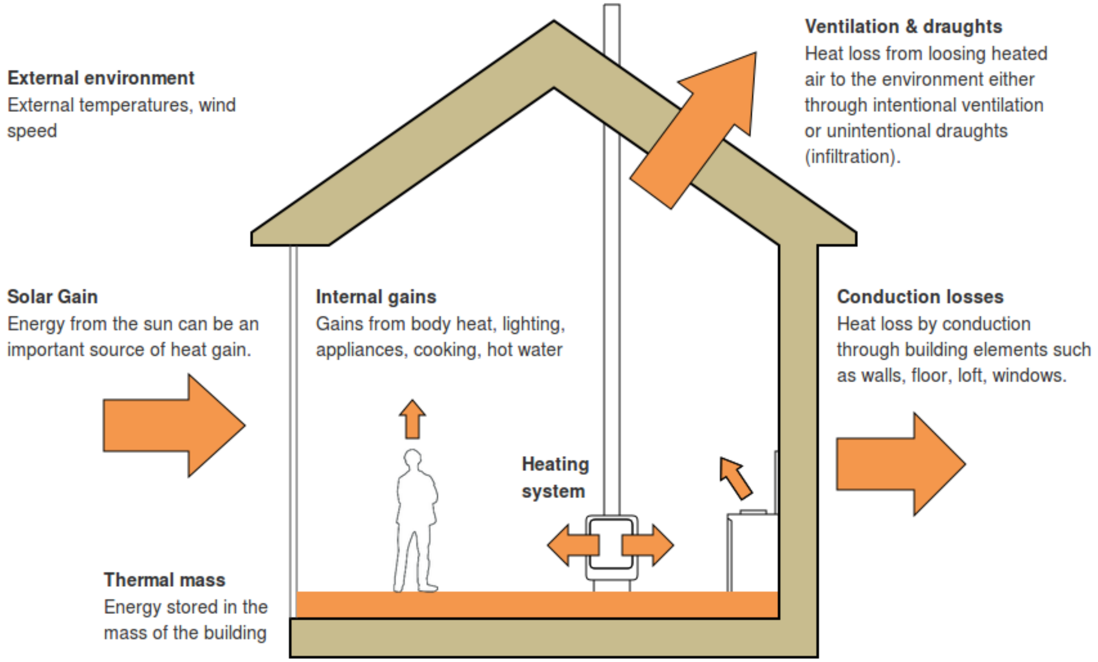
- Knowledge on data analysis and mathematical modeling.
- Good knowledge of at least one programming language.
- Patience, motivation, and curiosity.

Modeling and Model Development

What's a good model like?

- We use models to represent and investigate a phenomenon in real world or hypothetically
- Examples: building model, forestry model, energy and climate models etc.

- Elements of modeling work:
  - Structural relations (equations)
  - Data
  - States of the system (scenarios and simulation)
  - etc.



openenergymonitor.org

Question

What are the features of a good modeling tool?

What is the best practice in model development?

Everyone:

- Think about your experiences in the past and your expectations from this workshop
- List **three items** that are important to you **(2 min)**

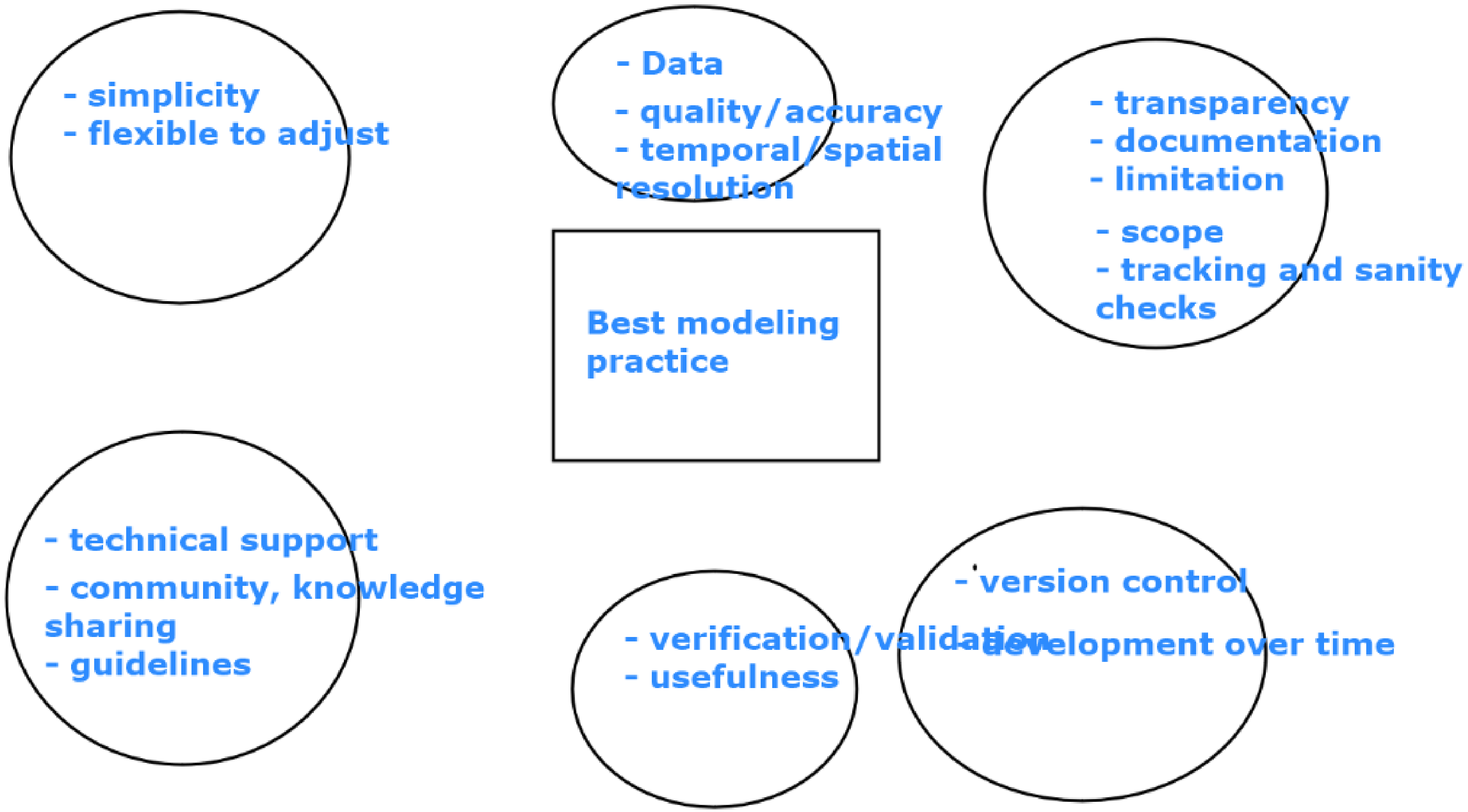
Group work (8 min):

- You will be grouped in parallel breakout sessions
- Possibly turn on your video, introduce yourself to each other
- Discuss your views on the questions

Question

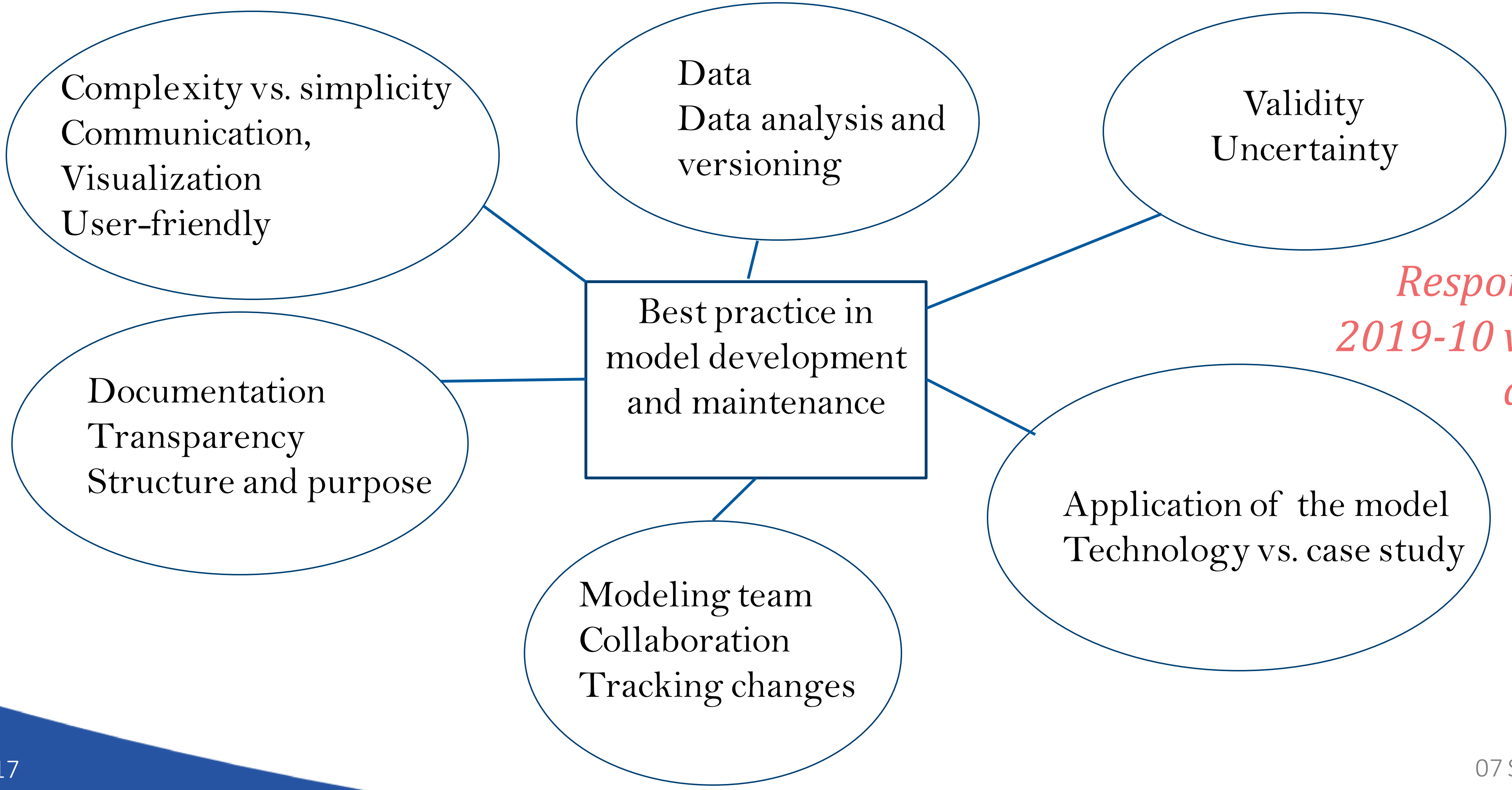
What are the features of a good modeling tool?

What is the best practice in model development?



Modeling and Model Development (2)

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



Responses from 2019-10 workshop attendees

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

Aim and vision of the framework as a whole

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:

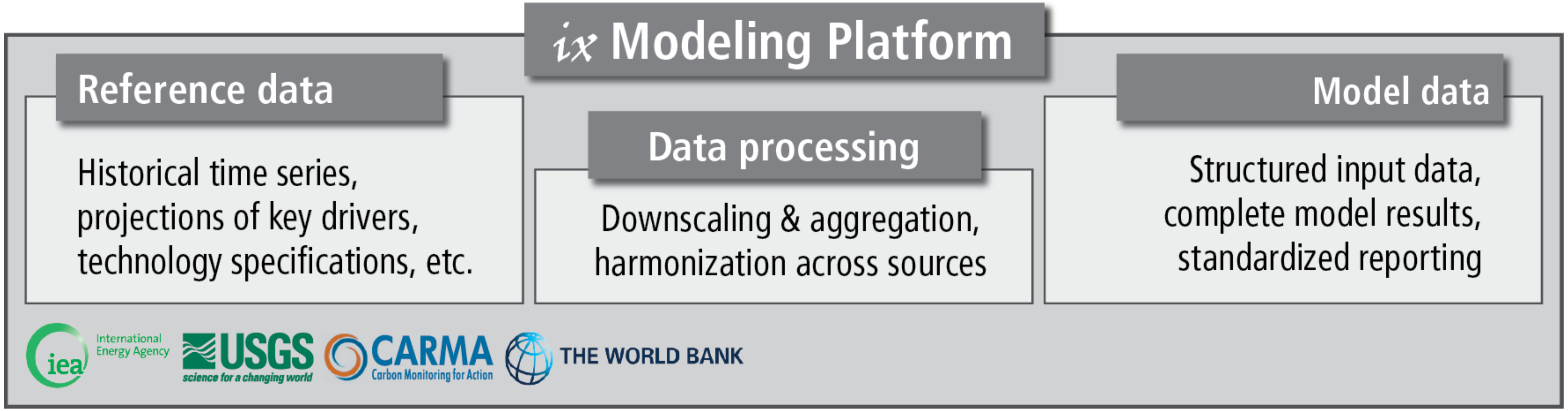
- integration of models & scientific analysis between different disciplines
- highest level of transparency and scientific reproducibility for a wide audience
- flexibility: across **spatial and temporal** levels of disaggregation

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

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

A central data management system (the ix modeling platform, ixmp)

- 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

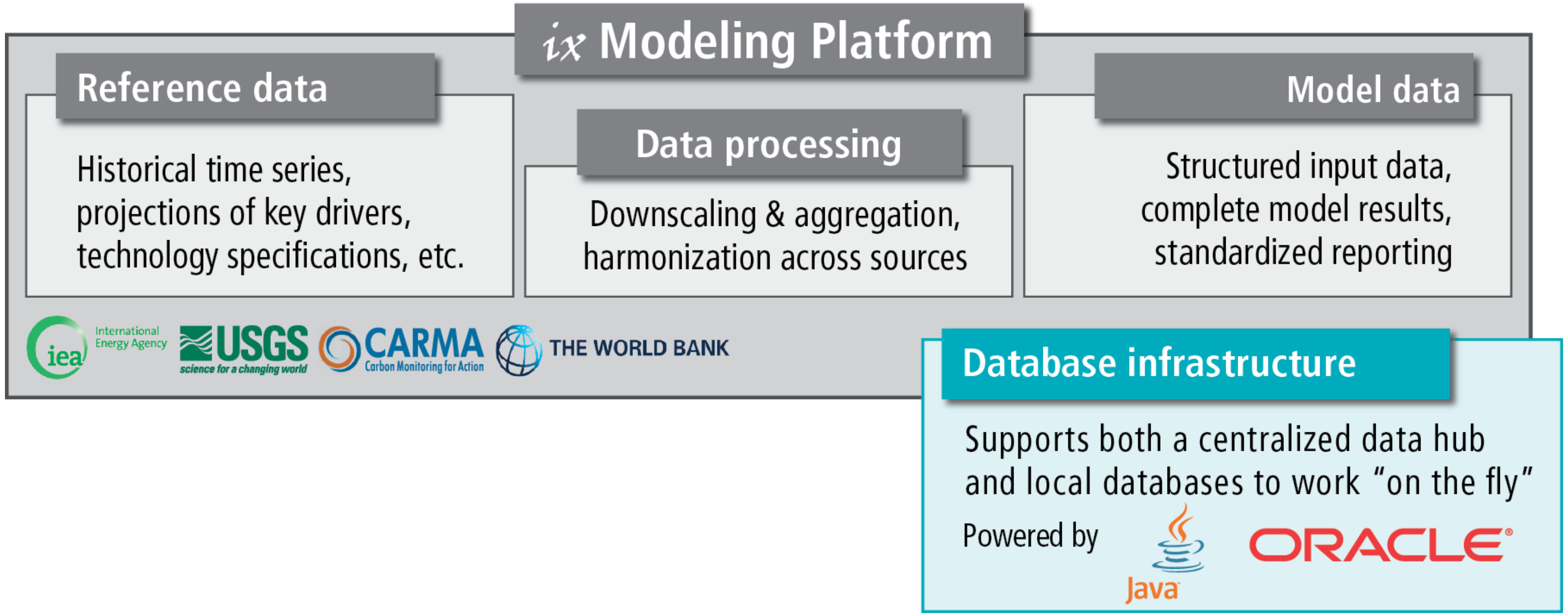
The MESSAGE$_{ix}$ modeling framework: 2. Database backend

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"



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

Connected to high-performance numerical programming

MESSAGE$_{ix}$ in 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*)

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

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

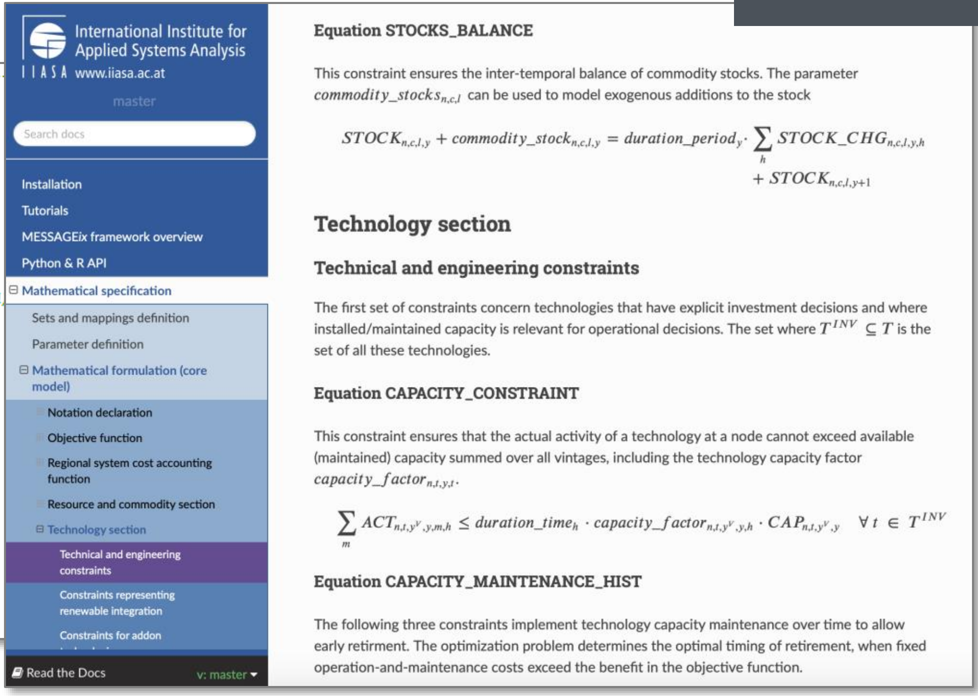
Implementing tools for comprehensive documentation

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) ;
```



Equation STOCKS_BALANCE

This constraint ensures the inter-temporal balance of commodity stocks. The parameter $commodity\_stocks_{n,c,l}$ can be used to model exogenous additions to the stock

$$STOCK_{n,c,l,y} + commodity\_stock_{n,c,l,y} = duration\_period_y \cdot \sum_h STOCK\_CHG_{n,c,l,y,h} + STOCK_{n,c,l,y+1}$$

Technology section

Technical and engineering constraints

The first set of constraints concern technologies that have explicit investment decisions and where installed/maintained capacity is relevant for operational decisions. The set where $T^{INV} \subseteq T$ is the set of all these technologies.

Equation CAPACITY_CONSTRAINT

This constraint ensures that the actual activity of a technology at a node cannot exceed available (maintained) capacity summed over all vintages, including the technology capacity factor $capacity\_factor_{n,t,y,t}$.

$$\sum_m ACT_{n,t,y^V,y,m,h} \leq duration\_time_h \cdot capacity\_factor_{n,t,y^V,y,h} \cdot CAP_{n,t,y^V,y} \quad \forall t \in T^{INV}$$

Equation CAPACITY_MAINTENANCE_HIST

The following three constraints implement technology capacity maintenance over time to allow early retirment. The optimization problem determines the optimal timing of retirement, when fixed operation-and-maintenance costs exceed the benefit in the objective function.

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

Interfaces to scientific programming for advanced users

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

Scientific programming API

Seamless integration with powerful, open and flexible scientific programming languages

✓ Efficient implementation of workflows

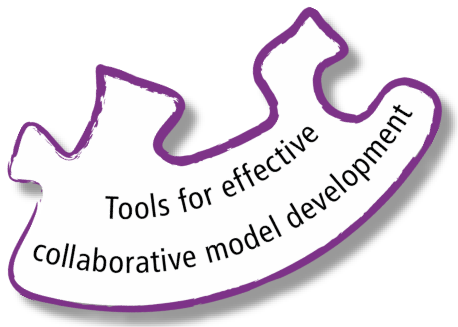
✓ Standardized interface for data processing

python™ R

The 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.



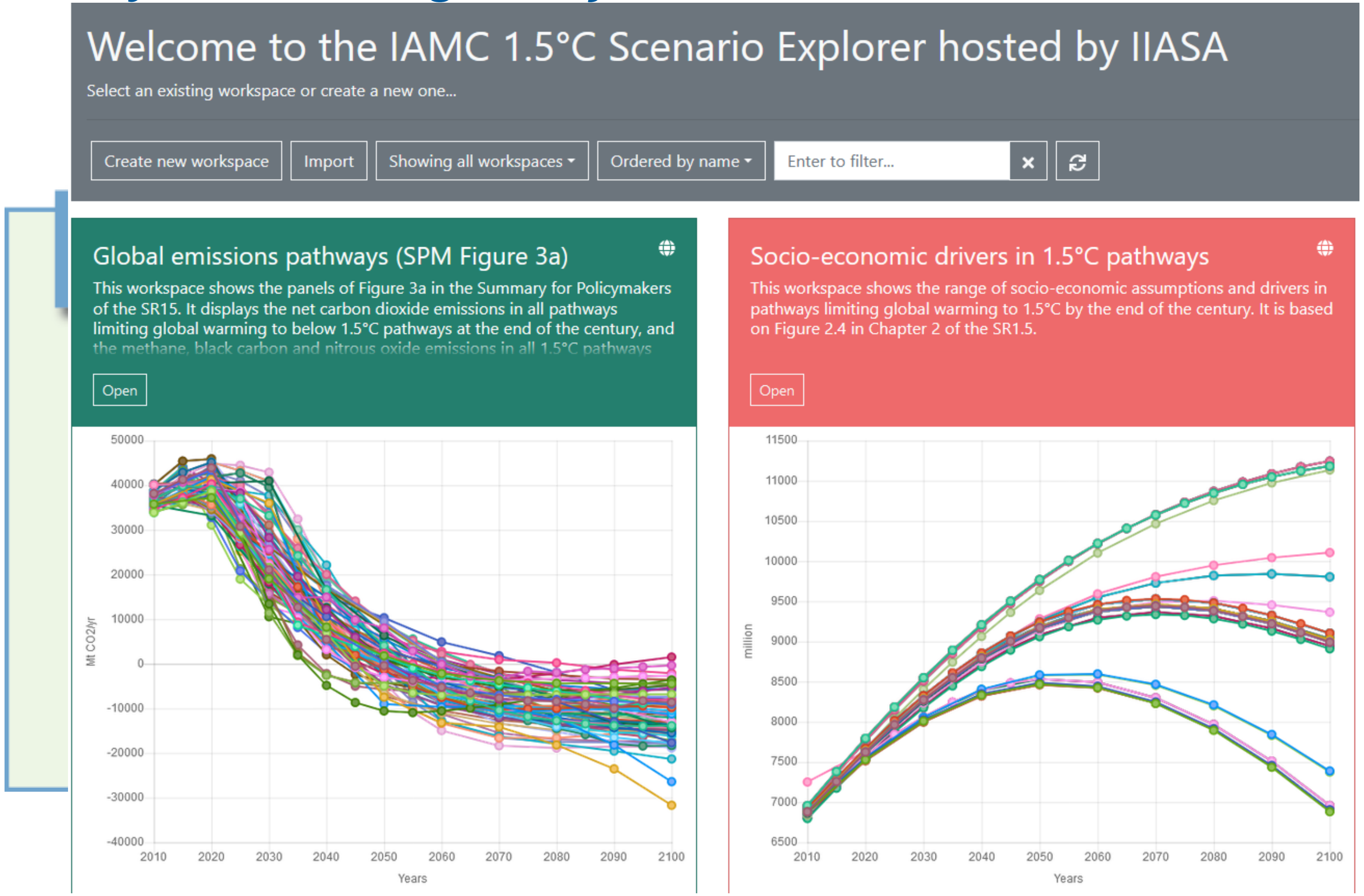
All contents of both MESSAGE$_{ix}$ and *ix*mp are **open-source** and online as GitHub repositories:

https://github.com/iiasa/message_ix
https://github.com/iiasa/ixmp/

In the last session of this workshop (Session IV) there will be more explanation on how to collaborate through GitHub.

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

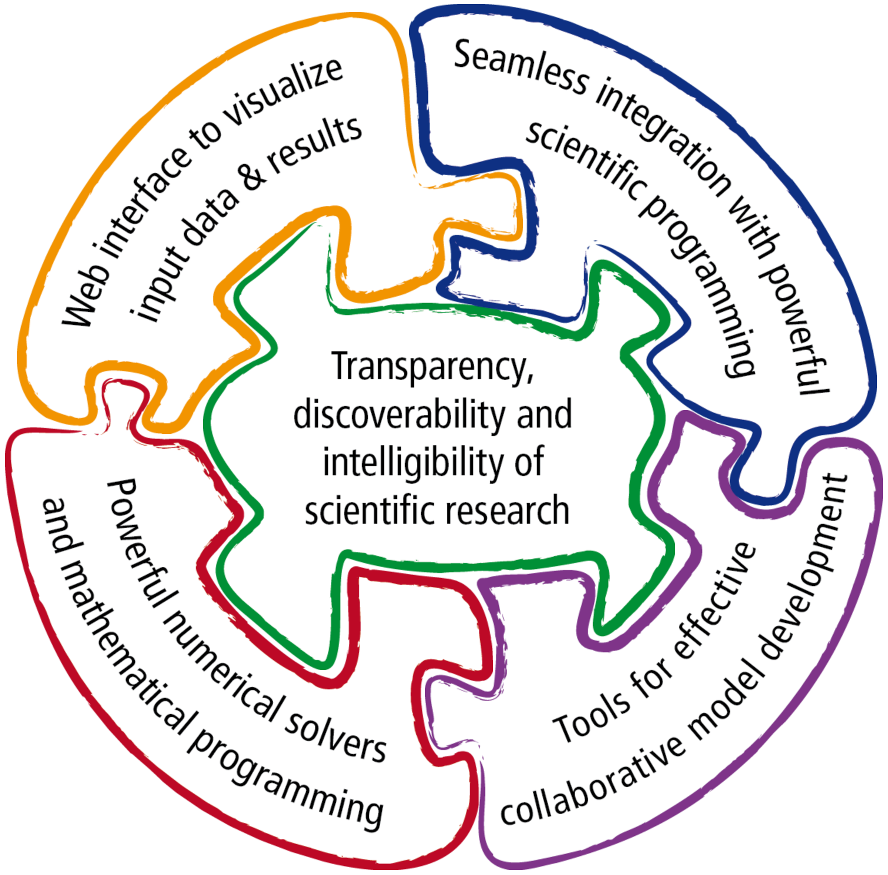
An intuitive gateway to modeling data for researchers and a wider audience



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

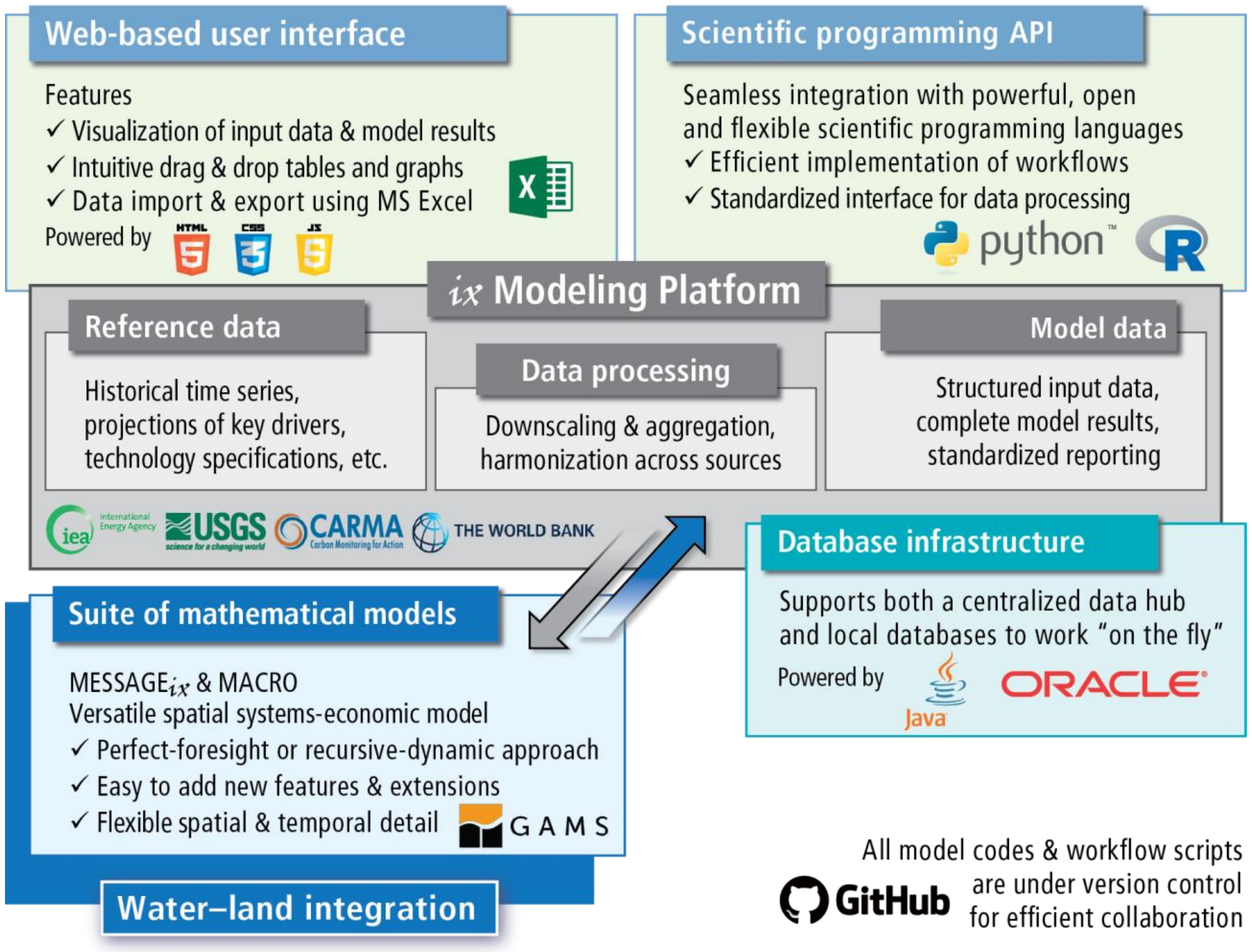
The MESSAGE$_{ix}$ modeling framework: Overview

Facilitating transparency and reproducibility of research



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

(Huppmann et al. 2019)

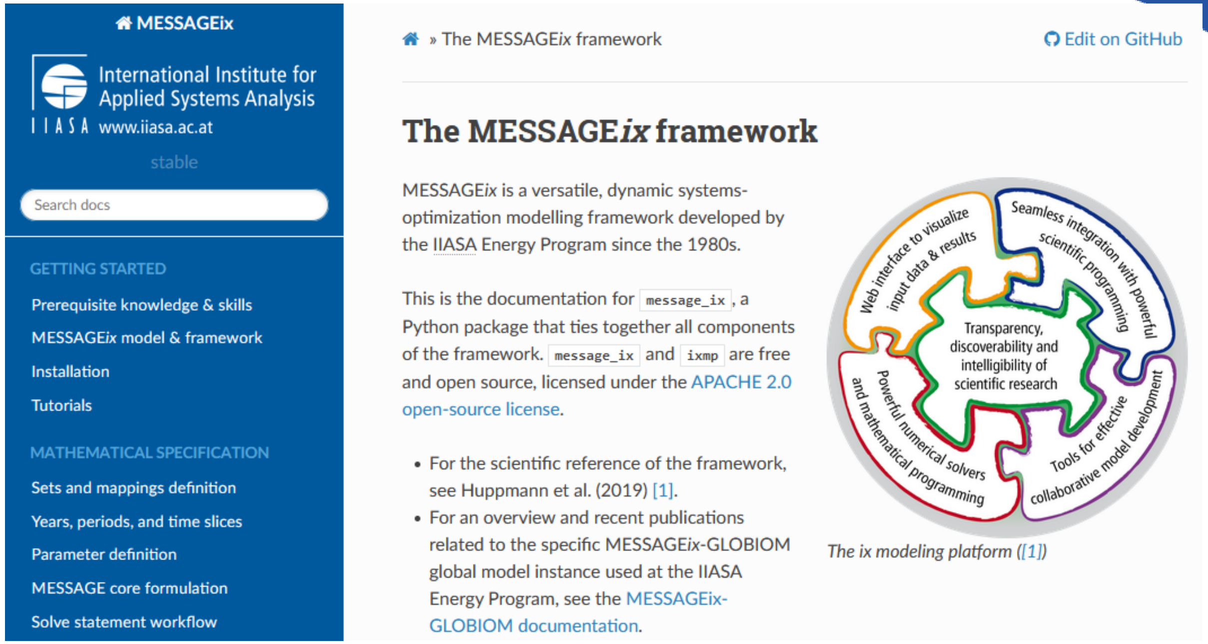


The MESSAGE$_{ix}$ modeling framework: Main sources of information

- 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:
  https://github.com/iiasa/message_ix/tree/master/tutorial



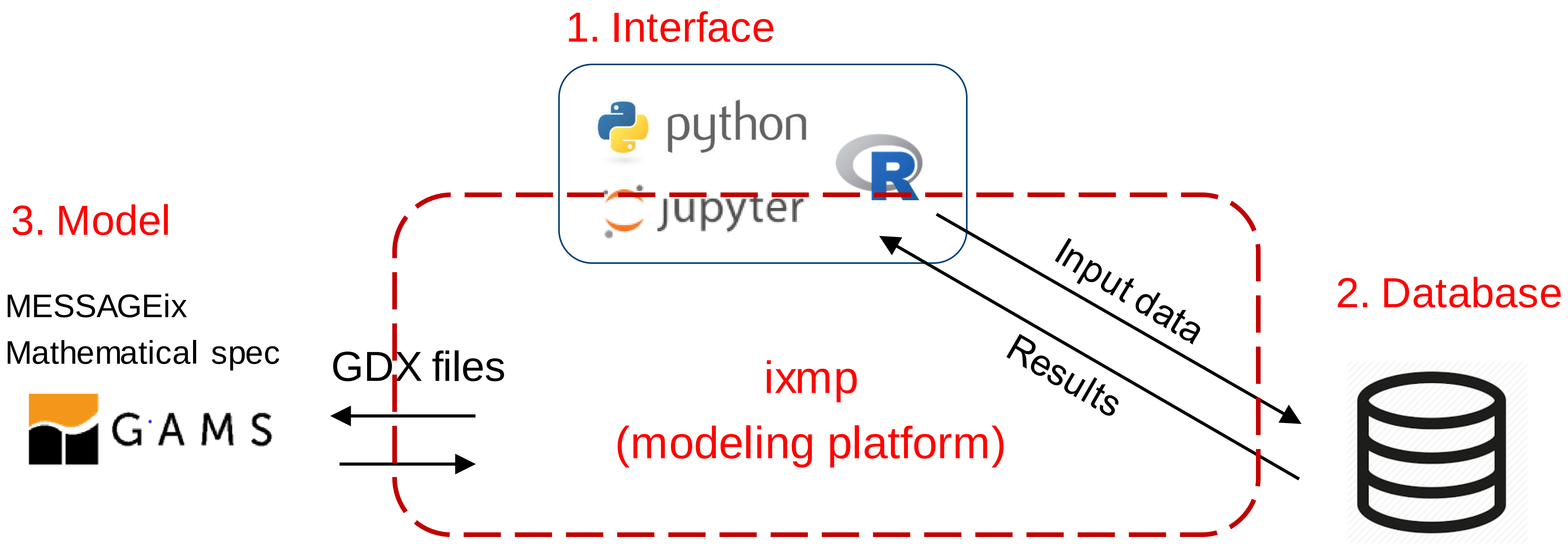
For more detailed information on *ix*mp:

- 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: 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.



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

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

```
message_ix
ixmp
```

python™

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

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

Two types of installation

1. Install MESSAGE$_{ix}$ through Anaconda

- You only want to use the public release (latest version is v3.1.0; ~every 6 months).
- You don't aim to contribute to the code on GitHub.
- Still possible to develop code and a model specific to your research needs.

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

- You want to test and review the latest features (i.e., since the latest public release).
- You want to contribute to the code.
- You want to (learn to) participate in collaborative code development.

Basic usage	Advanced usage
Install the released version of `message_ix`.	Install the development version (source code).
Use a laptop/desktop computer.	Use cloud computing/HPC servers.
Store data on your local machine.	Store data in a shared database.
Run/modify the tutorial notebooks.	Build large models from scratch.
	Collaborate on MESSAGEix-GLOBIOM.
Use the mathematical formulation as-is.	Modify the MESSAGE equations.
Use the `message_ix` Python/R code.	Contribute or request new features.

Link to installation page in ReadTheDocs: https://docs.messageix.org/en/stable/install.html

The MESSAGE$_{ix}$ modeling framework: Installation (2)

Installation through Anaconda. A checklist

1. Install the required software
   - Anaconda (add to PATH environment variable)
   - GAMS (add to PATH environment variable)

2. Install MESSAGE$_{ix}$
   - Open *Anaconda Prompt* window, and type:

```
$ conda config --prepend channels conda-forge
$ conda create -n my-env
$ conda activate my-env
$ conda install message-ix
$ conda install conda_nb
```

`message_ix` & `message-ix`:

- The actual name of the package installed is [message_ix]
- `message-ix` is a command-line program used to install and run tasks from [message_ix]

3. **Download tutorials** (examples for learning the model)

```
$ message-ix dl /path/for/folder_for_tutorials
```

The MESSAGE$_{ix}$ modeling framework: After installation

Check installation. What is where?

1. Check that installation was successful

- Verify that the version installed corresponds to the latest release by running the following commands on the command line:

```
$ message-ix show-versions
```

- If an error occurs, this may mean that an older version has been installed and should be updated

```
$ conda list message-ix
```

2. `ixmp` & `message_ix` Python packages

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

```
$ where conda
```

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

3. Mathematical model folder

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

Open an *Anaconda Prompt* window, and type:

```
$ message-ix copy-model /path/for/GAMS/files
```

The MESSAGE$_{ix}$ modeling framework: Mathematical formulation

Everything is at your disposal!

Looking into the GAMS files

- Locate your “model” folder (for example, *C:\...\message_ix\message_ix\model*)
- Create a GAMS project there to work with the files more easily (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

193	addon_up	Par	6	6,822
163	aeei	Par	3	726
44	balance_equality	Set	2	0
106	bound_activity_lo	Par	5	8,053
105	bound_activity_up	Par	5	11,845
136	bound_emission	Par	4	0
82	bound_extraction_up	Par	4	88
102	bound_new_capacity_lo	Par	3	150
101	bound_new_capacity_up	Par	3	4,098
104	bound_total_capacity_lo	Par	3	0
103	bound_total_capacity_up	Par	3	0
85	capacity_factor	Par	5	116,559
42	cat_addon	Set	2	29
32	cat_emission	Set	2	16
29	cat_node	Set	2	11
33	cat_relation	Set	2	0

				1990	1995	2000	2005	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110
bio_istig	M1	year	cogeneration_heat					0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
bio_istig_ccs										0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
bio_ppl					0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
			scrubber_CO2_bio		0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
cement_CO2			scrubber_CO2_cement	0.28	0.28	0.28	0.25	0.23	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
coal_adv			cogeneration_heat					0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	lignite							0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
coal_adv_ccs	M1								0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	lignite								0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
coal_ppl	M1				0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
			scrubber_CO2_coal		0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
	lignite		cogeneration_heat		0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
			scrubber_CO2_coal		0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
coal_ppl_u	M1		cogeneration_heat	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15							
	lignite			0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15							

Thank you very much for your attention!

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