International Institute for Applied Systems Analysis
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TU WIEN

Lecture 4: Developing your own energy system scenarios

Open-Source Energy System Modeling
TU Wien, VU 370.062

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Part 1

A high-level overview of the open-source energy system model MESSAGE$_{ix}$

Before we get started...

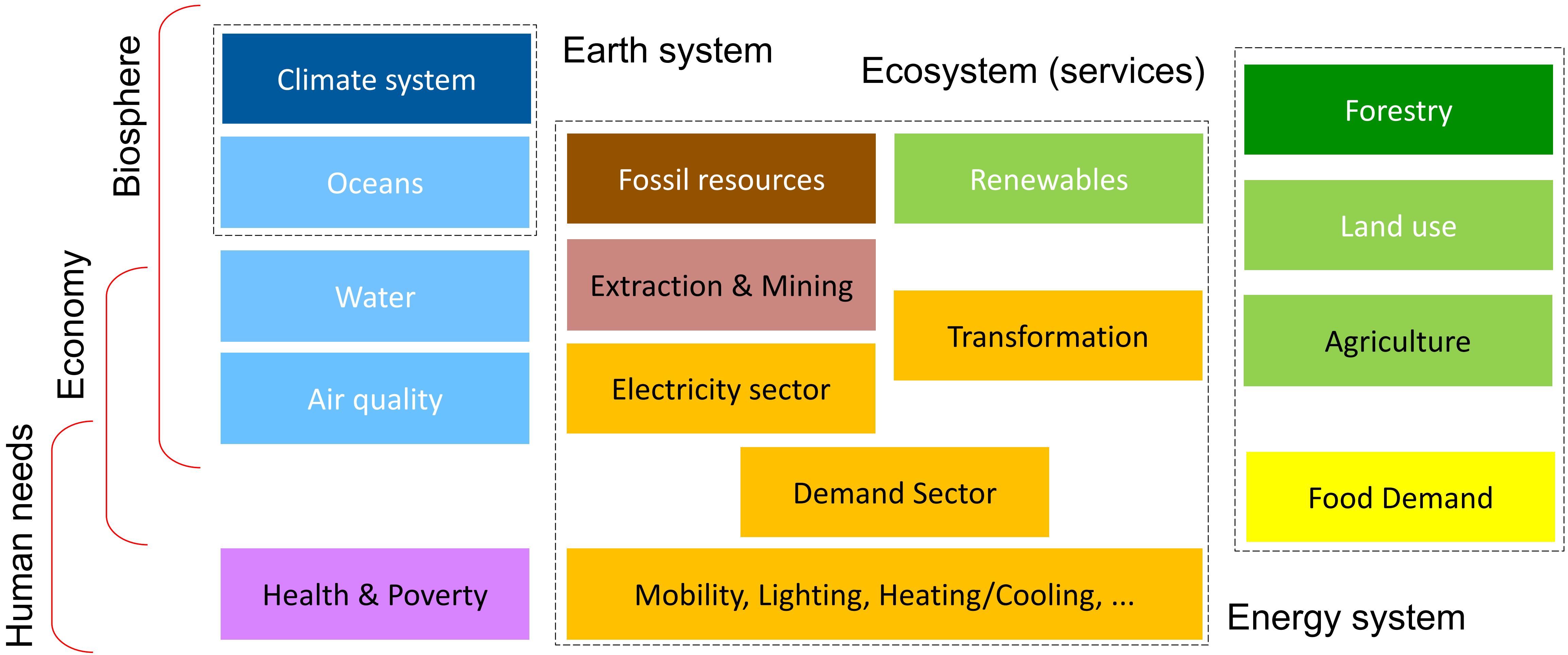
What's a "model"?

- An attempt at a definition (in the context of energy systems):
  - ⇒ A stylized representation of reality
  - ⇒ Clear definition of the system boundaries
  - ⇒ Based on a mathematical description
  - ⇒ Parametrized and solved numerically
- In practice, the terms **model** & **scenario** are used for several of the items below:
  - ⇒ Mathematical formulation – "just the **equations**"
  - ⇒ Scientific software implementing the equations (but without data) – **modelling framework**
  - ⇒ A **model** implemented in a modelling framework including full "baseline" parametrization
  - ⇒ A **scenario design** or **scenario protocol** is a narrative and parametrization of assumptions

    possibly relative to the baseline
  - ⇒ A **scenario** is an implementation of a scenario protocol in a model

Some practical considerations for starting model development

Make a conscious choice concerning the system boundaries of your work



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

An integrated modeling platform for x-cutting analysis

An effort started in 2016 – and still ongoing...

Goal: Develop a platform for streamlined modeling

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

⇒ building versatile & powerful mathematical models,

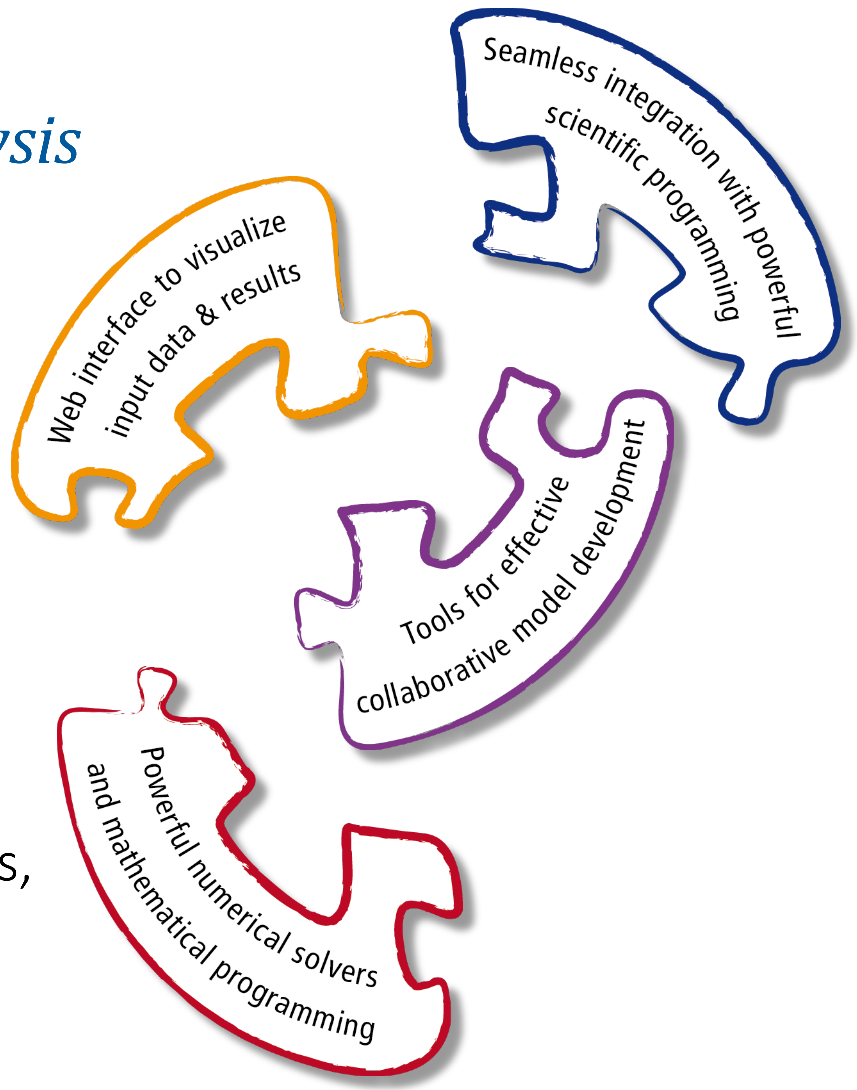
⇒ applying best practice of collaborative research

Vision: Facilitate integration of models & scientific analysis

... between different disciplines and fields including economics, engineering, geophysical, and social sciences

... across spatial and temporal levels of disaggregation

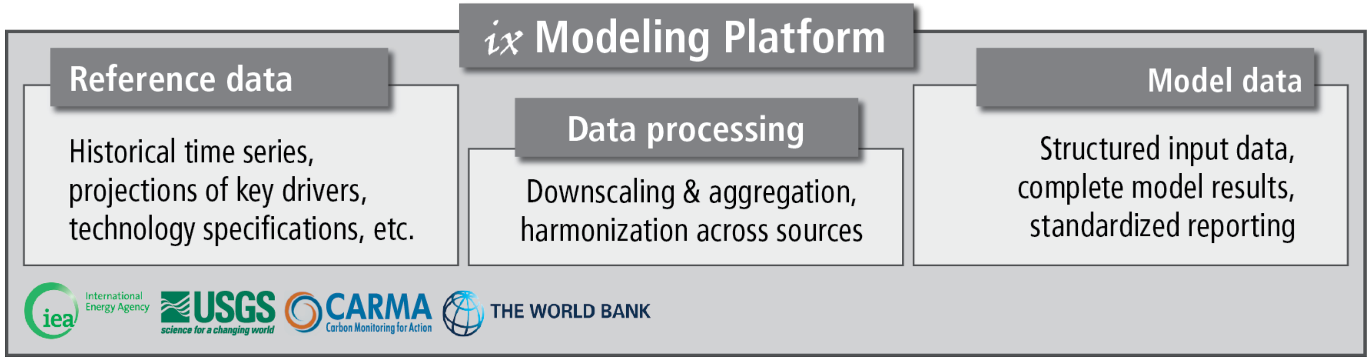
... while guaranteeing the highest level of transparency and scientific reproducibility for a wide audience



Key features of the *ix* modeling platform

The MESSAGE*ix* framework: Data management

A central data management warehouse



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

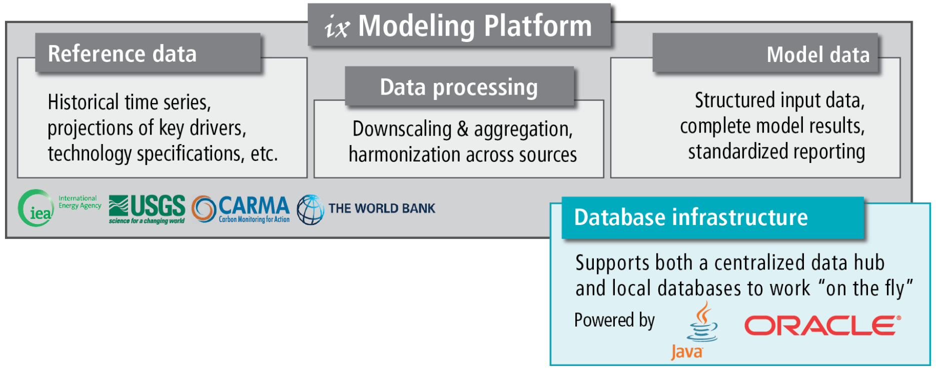
The MESSAGE$_{ix}$ framework: Database backend

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"

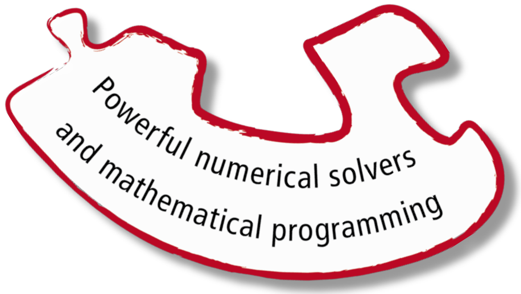


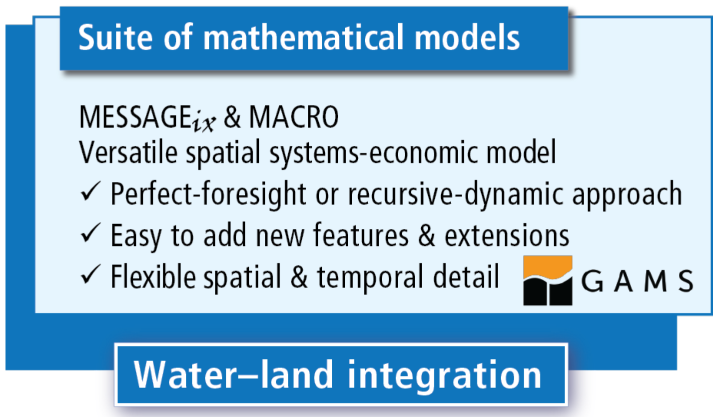
The MESSAGE$_{ix}$ framework: Integration with GAMS

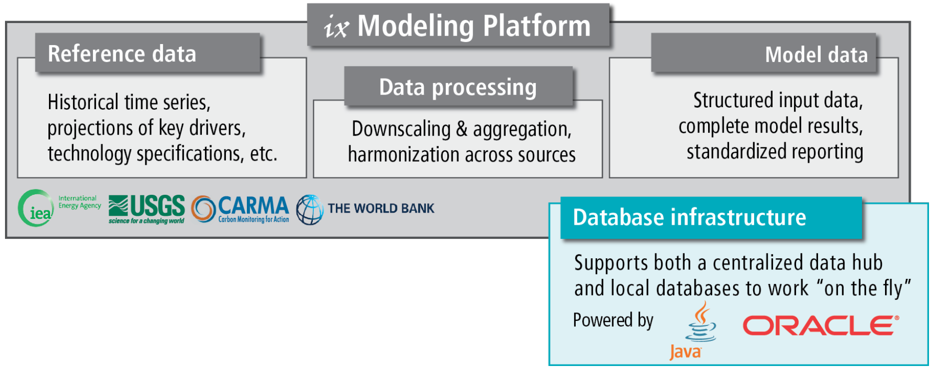
Connected to high-performance numerical programming

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

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







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

Interfaces to scientific programming for advanced users

```
In [1]: import ixmp

In [2]: # launch the IX modeling platform
        using the local default database
        mp = ixmp.Pl

In [3]: model = "Au
        scen = "bas
        annot = "st

        scenario =

        annotation=
             scheme=

In [4]: horizon = r
        firstyear =

In [5]: scenario .a
        scenario .a
        "firstmodel

In [6]: country = "
        ds.add_set(
```

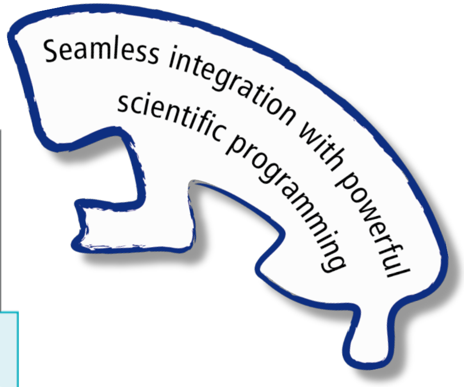
python

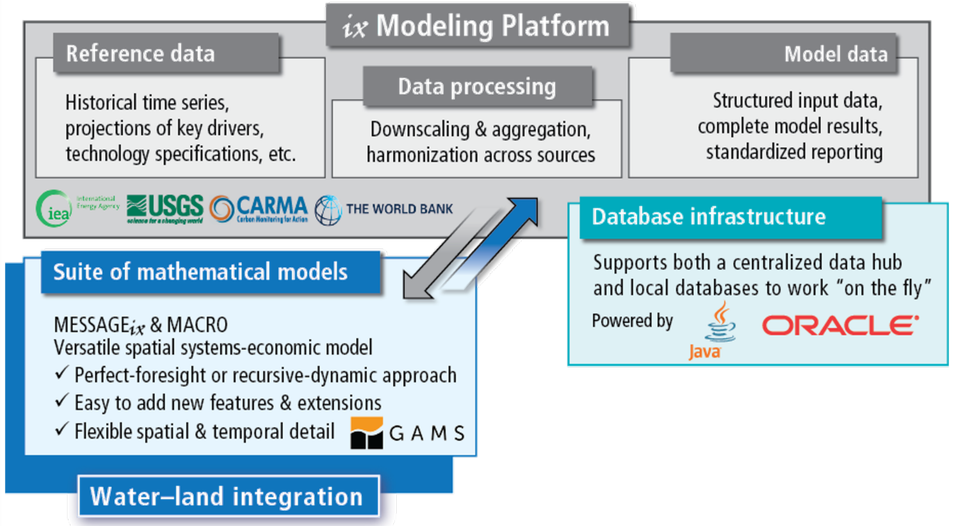
```r
#-----------------------------------------
# load package

require('Rixmp')

# launch the IX modeling platform
mp <- Platform()

#-----------------------------------------
# specify the model and scenario name

model <- "canning problem"
scen  <- "standard“

#-----------------------------------------
# load a datastructure from the database

scenario <- mp$Scenario(model, scen)

#-----------------------------------------
# retrieve the demand as a dataframe

demand <- scenario$par("demand")
```

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 MESSAGEix framework: Collaborate research

Geared towards best-practice in collaborative research

The platform facilitates collaborative model development

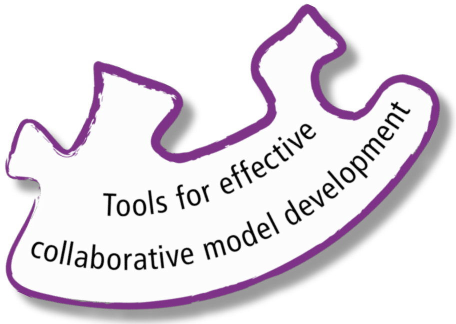
... through comprehensive data version control

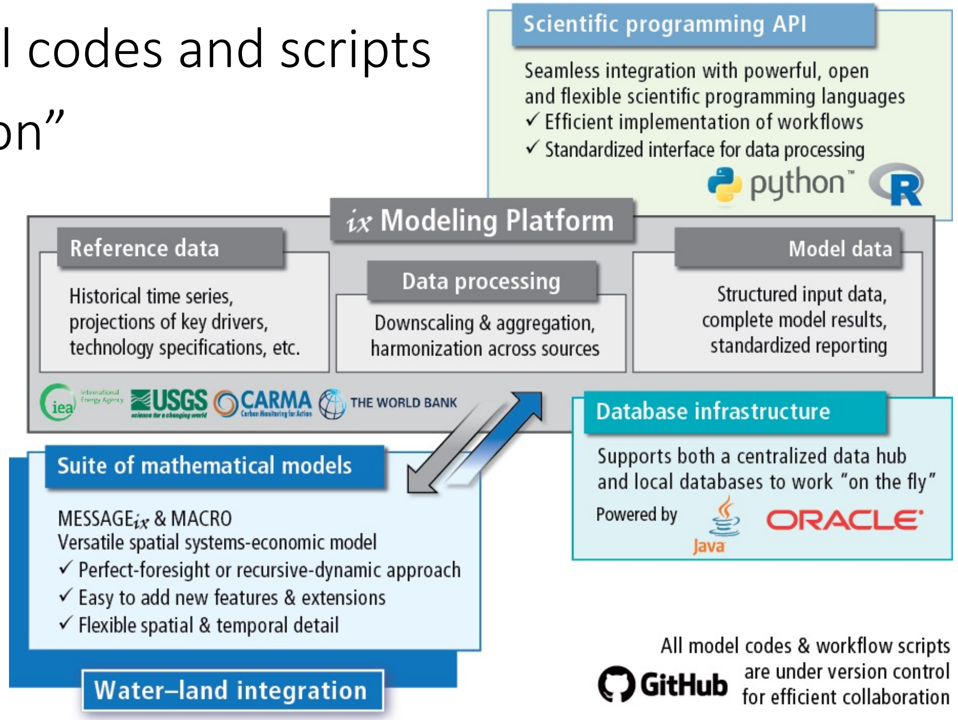
... by moving to “script-based” data processing & analysis

... using full version control of all model codes and scripts

... implementing “continuous integration”

⇒ automated testing of new features
to ensure stable code base





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) ;
```

GAMS

Read the Docs

Scientific programming API

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master

Search docs

- Installation
- Tutorials
- MESSAGEix framework overview
- Python & R API
- Mathematical specification
  - Sets and mappings definition
  - Parameter definition
  - Mathematical formulation (core model)
    - Notation declaration
    - Objective function
    - Regional system cost accounting function
    - Resource and commodity section
    - Technology section
      - Technical and engineering constraints
      - Constraints representing renewable integration
      - Constraints for addon

Read the Docs v: master

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 $capacity\_factor_{n,t,y,t}$.

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

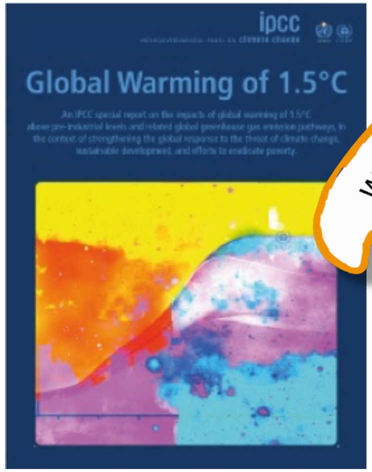
Equation CAPACITY_MAINTENANCE_HIST

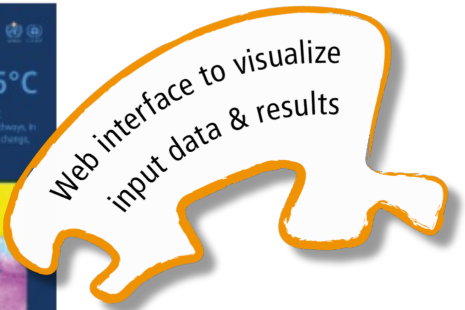
The following three constraints implement technology capacity maintenance over time to allow early retirement. The optimization problem determines the optimal timing of retirement, when fixed operation-and-maintenance costs exceed the benefit in the objective function.

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

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

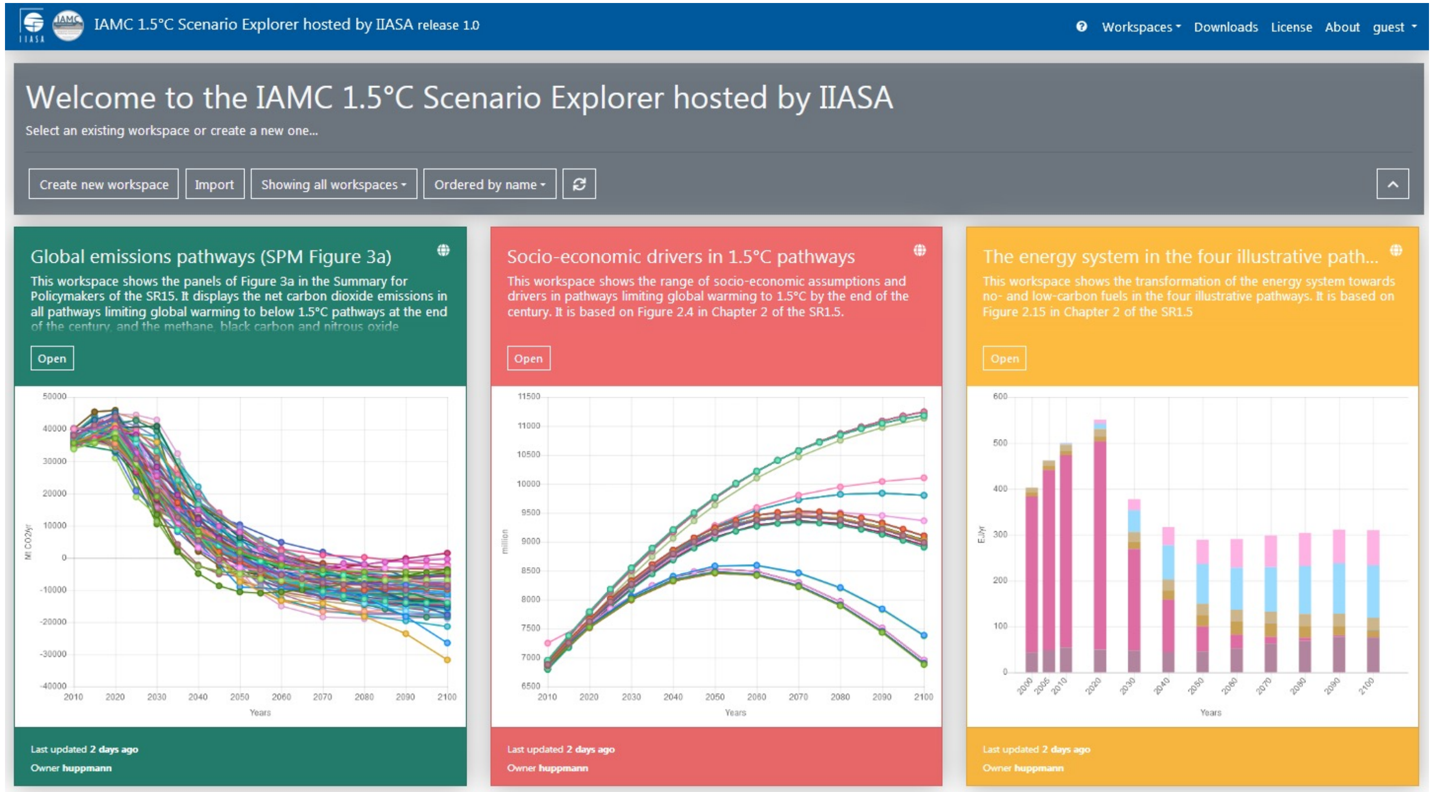
The "IAMC 1.5°C Scenario Explorer" presenting an ensemble of pathways supporting the IPCC SR15 assessment is powered by the web user interface of the *ix* modeling platform





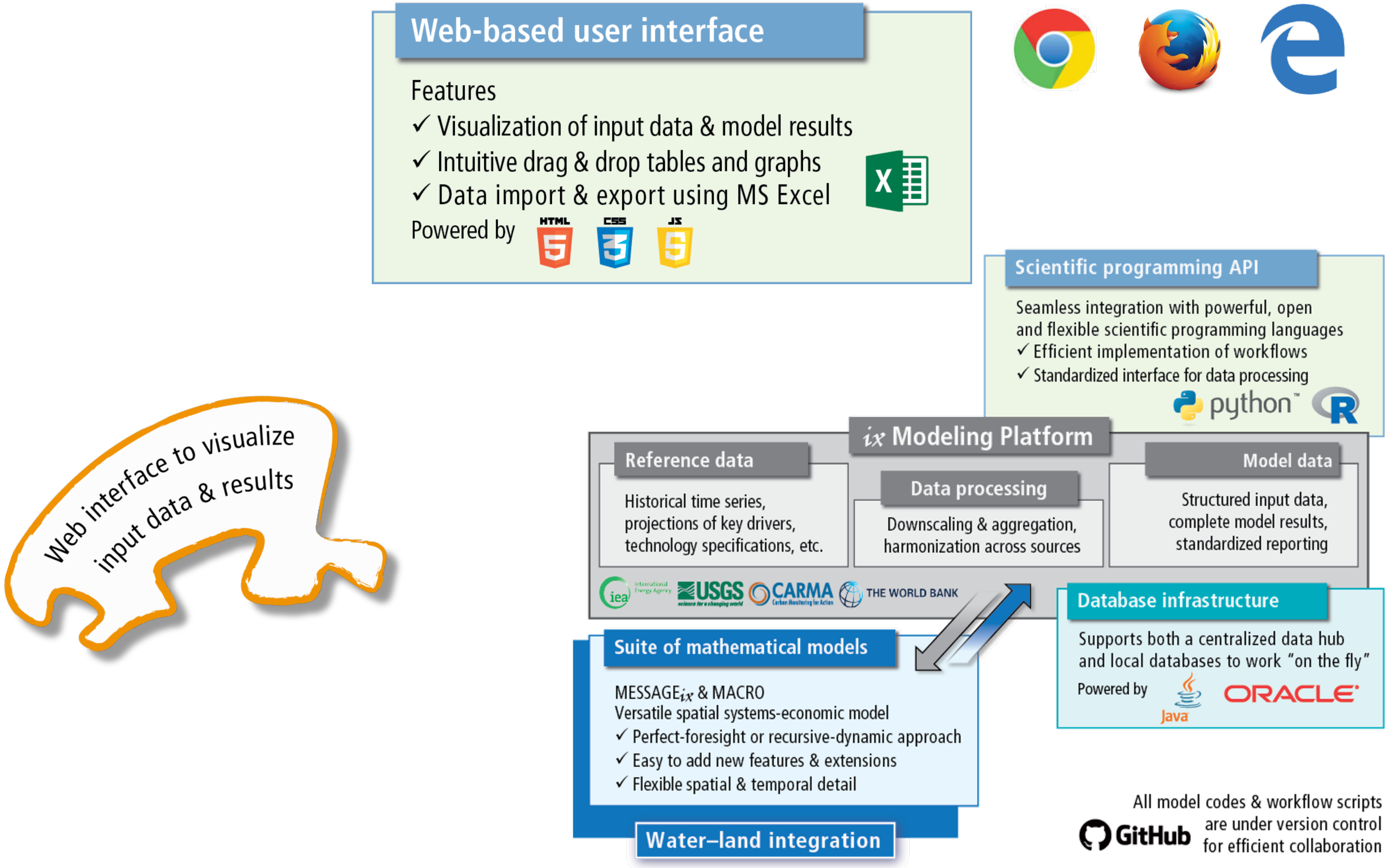
Special Report on *Global Warming of 1.5°C* (IPCC SR15, http://www.ipcc.ch/report/sr15/)

Visit the Scenario Explorer at https://data.ene.iiasa.ac.at/iamc-1.5c-explorer



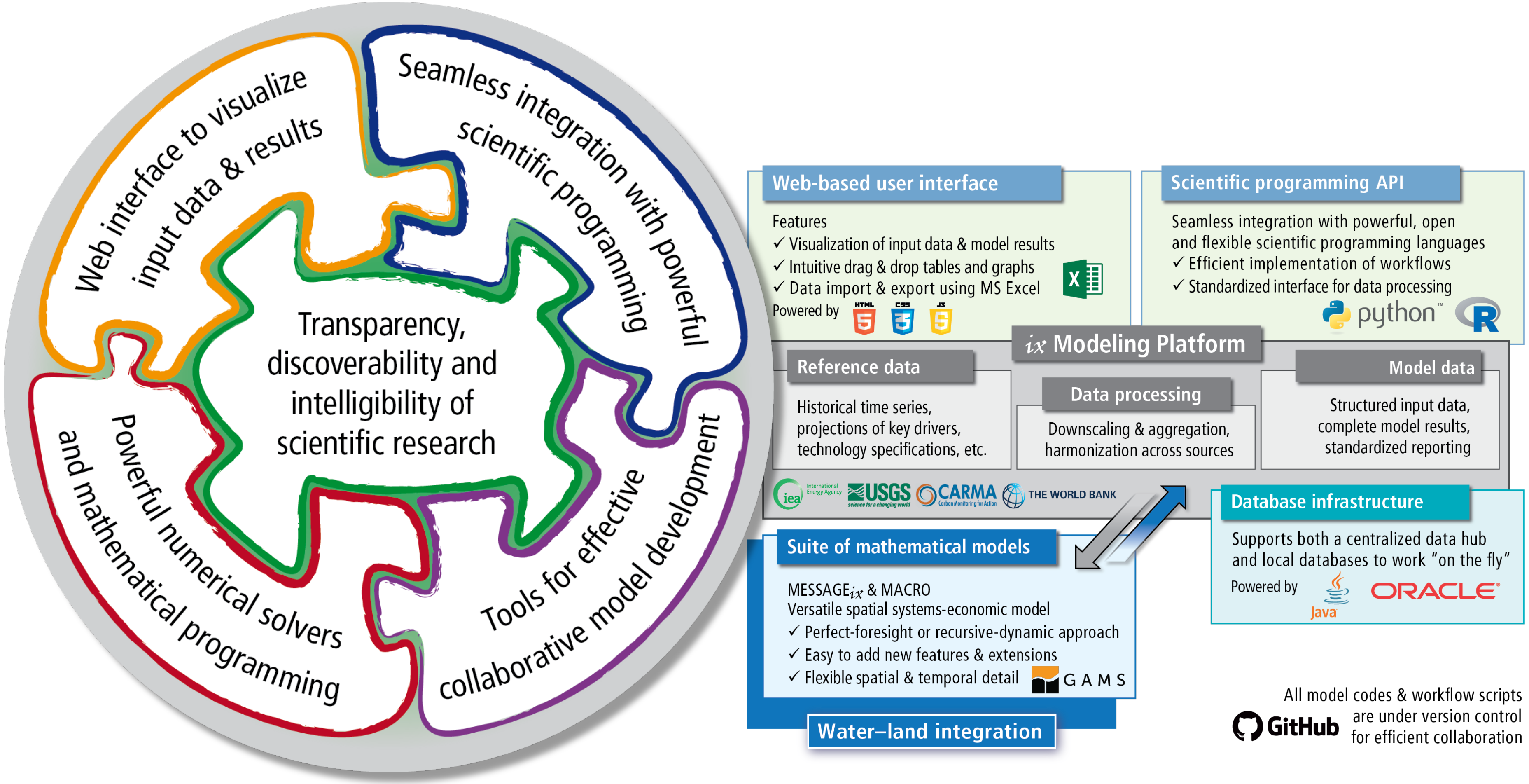
The MESSAGE$_{ix}$ framework: Interactive web user interface

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



The MESSAGE$_{ix}$ framework

Facilitating transparency and reproducibility of research



Working with the MESSAGE$_{ix}$ framework

Practical considerations where MESSAGE$_{ix}$ differs from other frameworks

Installation:

⇒ When installing public release versions via pip or anaconda, you don't need to worry

⇒ To get the bleeding-edge developments, make sure that you install the corresponding branches from the GitHub repositories `ixmp` and `message_ix`

⇒ Known issue on Mac: `versioneer` is sometimes confused, delete installation from `site-packages` directory manually if necessary

Your scientific workflow:

⇒ Don't re-run your scenario assessment notebooks over and over again, because this will create a new scenario instance in the database every time

⇒ Instead, remove the ``version=new`` argument to load an existing scenario and adapt the script accordingly

Working with the MESSAGE$_{ix}$ framework

Practical considerations where MESSAGE$_{ix}$ differs from other frameworks

Integration with GAMS:

⇒ The GAMS code is installed (copied) to the Python `site-packages` directory, so if you make changes in your `git` folder, it won't have any effect on your model run

⇒ This actually makes a lot of stuff simpler for the Python installation (say @gidden and @khaeru)

⇒ But you can set your `git` folder as the model folder

(i.e., where the `message_ix` package looks for the MESSAGEix-GAMS code)

using this command line interface (CLI):

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

Part 2

How to start developing your own energy system scenarios?

Considerations for developing a new (energy system) model

What do you need to build an energy system

- A “reference energy system” (RES)
  - ⇒ The technologies, commodities, levels
- Regional specification
- Time horizon
- Assumptions (projections)
  - ⇒ Costs (investment, capacity, variable)
  - ⇒ Demand for energy and other commodities
  - ⇒ Bounds on trade, diffusion of new technologies, etc.
- Policies on emissions (taxes, bounds) and sustainable development policies

To make learning MESSAGEix more fun, we developed a suite of tutorials based on the TV show “Game of Thrones”

Homework assignment

Let there be light in Westeros (while reducing CO2 emissions)

Create new notebook(s) starting with a clone of the MESSAGEix Westeros tutorial baseline answering one of the two research questions below. The answer should implement several scenarios as sensitivity analysis. Invitation to collaborate due by Monday, May 31, 23:59.

- Add a new technology for LEDs (which is more expensive than light bulbs per energy service)
  - ⇒ Show that the results of the baseline scenario do not change
  - ⇒ Investigate under which carbon price the LED technology becomes economically viable
  - ⇒ Assume different maximum diffusion rates for this new technology and compare the share of electricity from coal and wind depending on the diffusion rates
- Add a new technology "gas power plant"
  - ⇒ Assume realistic cost parameters and lifetimes for this power plant type (include references your sources in the notebook)
  - ⇒ Is there a "sweet spot" of prices on carbon such that coal, wind & gas are used at the same time?

The notebooks should not just show one solution, but illustrate/document your solution approach

Part 3

Some considerations on modelling

More practical considerations for starting model development

Choose an appropriate methodology for the research question at hand

Commonly used methodologies:

⇒ Optimization: determine the system that is optimal according to a metric

⇒ Equilibrium: determine the system as a result of interacting agents

⇒ Simulation: determine the system given some decision rules

Dealing with uncertainty:

⇒ Deterministic optimization (perfect foresight):

all future states (exogenous parameters) are known at the beginning of the model horizon

⇒ Stochastic optimization:

all future states along an "uncertainty tree" are known, including probabilities of each branch

⇒ Myopic (rolling horizon) optimization:

- decisions in period y are taken under some assumptions about the future;
- move to period $y + 1$ and repeat, with (possibly altered) assumptions about periods $[y + 2, \dots]$

Yet more practical considerations for starting model development

There are many issues that a self-critical modeller should consider...

- Model uncertainty:
  ⇒ Is the approach appropriate? Are results dependent on the methodology?
- Parameter uncertainty:
  ⇒ How much confidence can you have on input assumptions?
- Model horizon and level of temporal/spatial disaggregation:
  ⇒ What is the intended scope of analysis? Beware of the "end-of-horizon"-effect!
- Model simplifications for numerical tractability and comprehensibility:
  ⇒ What are appropriate trade-offs between having a high level of detail vs. loosing focus?
  E.g., variable renewables require infrastructure for system stability – assumption or result?
- System boundaries and model closure:
  ⇒ Are the assumptions to "close" the model valid?
  E.g., for a national electricity model, you need to make assumptions about import/export

Methods to evaluate the robustness of results

Think hard about testing your model behaviour

Methods for validation:

- Sensitivity analysis:
  Structured variation of key input parameters to understand the impact on results

  ⇒ Relatively easy to do, but you can never do sensitivity assessment for all parameters...

- Multi-criteria analysis:
  Include multiple dimensions in the objective function, solve model with different weights

  ⇒ Requires some work, still prone to modelling artefacts

- “Modelling to generate alternatives”
  Re-solve a model to get a different solution within some additional bounds

  ⇒ Very elegant, but requires substantial effort to implement

  Further reading: Joseph F. DeCarolis. Using modeling to generate alternatives (MGA) to expand our thinking on energy futures. *Energy Economics* 33(2):145-152, 2011. doi: [10.1016/j.eneco.2010.05.002](https://doi.org/10.1016/j.eneco.2010.05.002)

Thank you very much for your attention!

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