International Institute for
Applied Systems Analysis
IIASA www.iiasa.ac.at

TU WIEN

Lecture 4:
Developing your own energy system scenarios

Open-Source Energy System Modeling
TU Wien, VU 370.062

Dipl.-Ing. Dr. Daniel Huppmann

Please consider the environment before printing this slide deck

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

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

An ix 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,

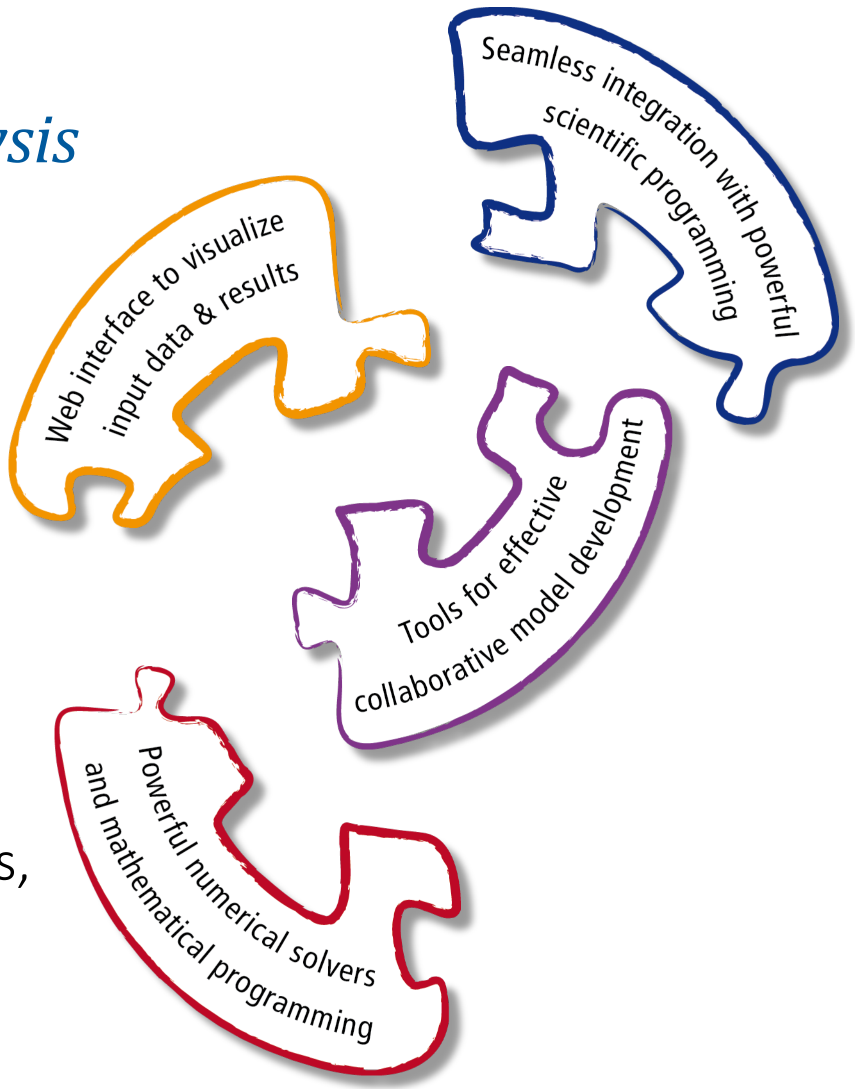
⇒ applying best practice of collaborative research

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

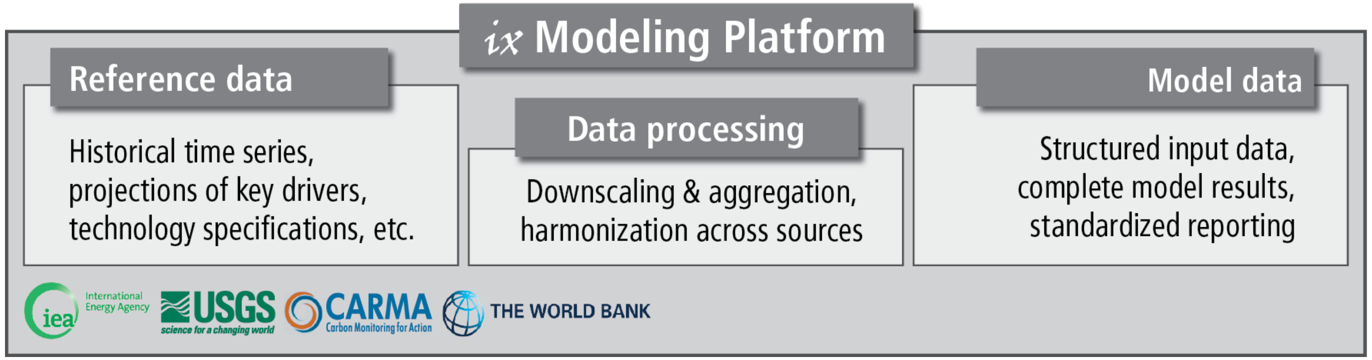
... while guaranteeing the highest level of transparency and scientific reproducibility for a wide audience


Seamless integration with powerful scientific programming
Web interface to visualize input data & results
Tools for effective collaborative model development
Powerful numerical solvers and mathematical programming

Key features of the *ix* modeling platform

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

A central data management warehouse


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

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

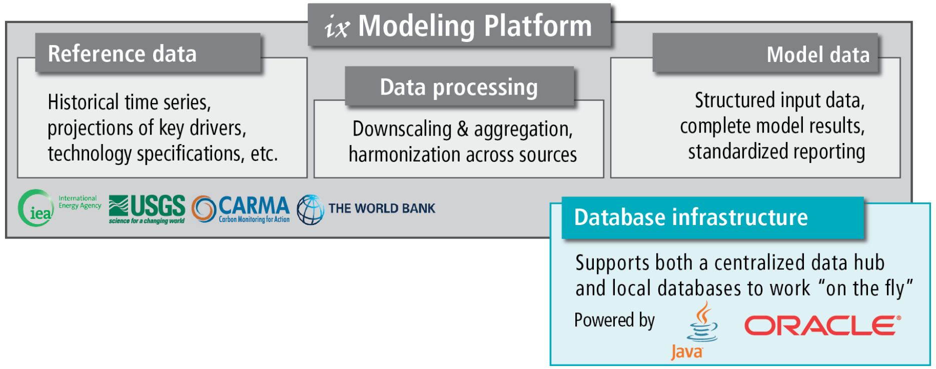
The MESSAGE$_{ix}$ framework: Database backend

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”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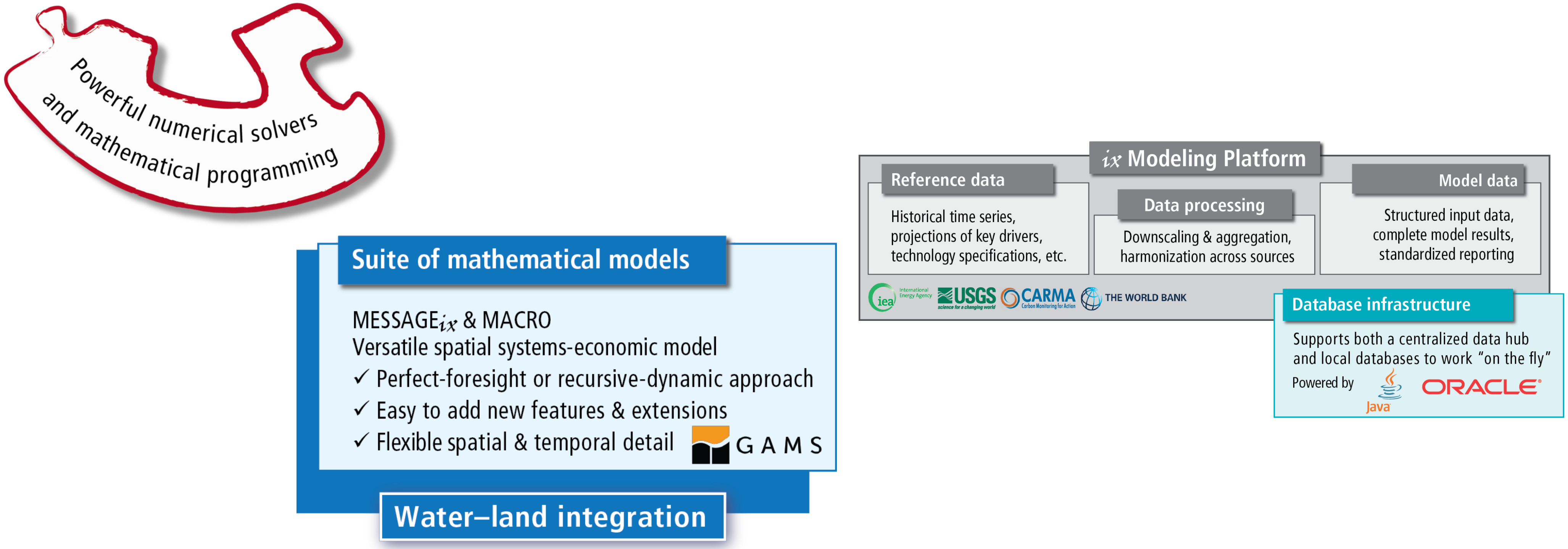
Powered by
Java
ORACLE

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...



Powerful numerical solvers and mathematical programming

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

***ix* Modeling Platform**

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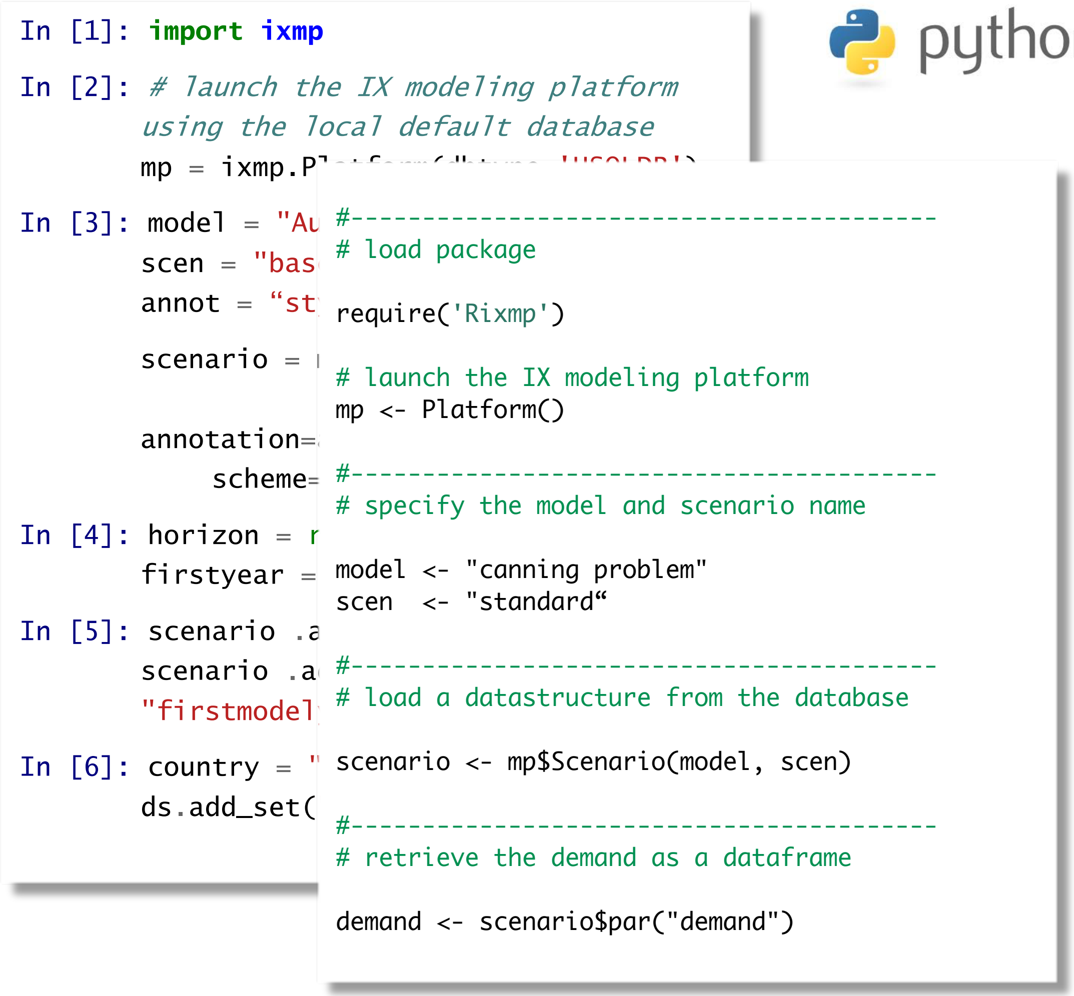
Powered by Java ORACLE

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.Platform(dbtype='HSQLDB')

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

        scenario = i

        annotation=
             scheme=
In [4]: horizon = r
        firstyear =

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

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

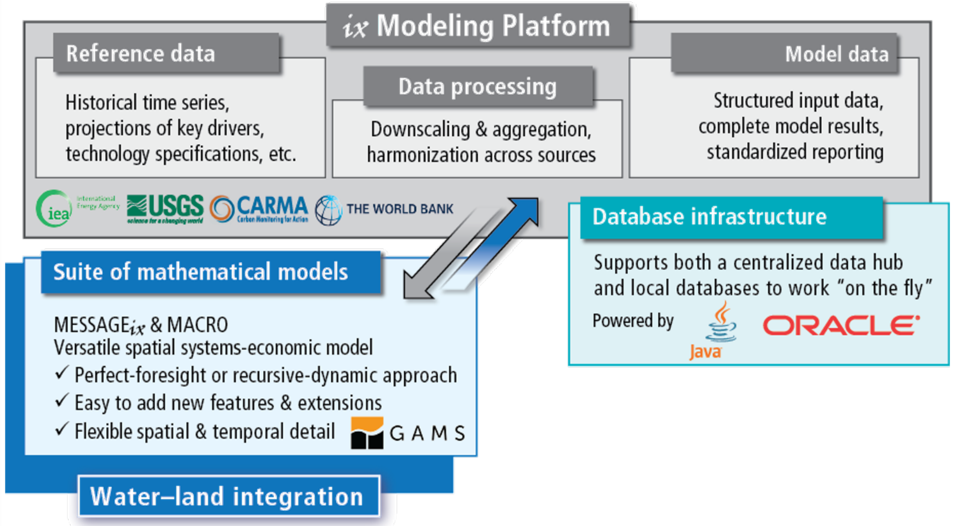
```
#----------------------------------------
# load package

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



ix Modeling Platform

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Powered by

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Water–land integration

Seamless integration with powerful scientific programming

The MESSAGEix framework: Collaborate research

Geared towards best-practice in collaborative research

The platform facilitates collaborative model development

… through comprehensive data version control

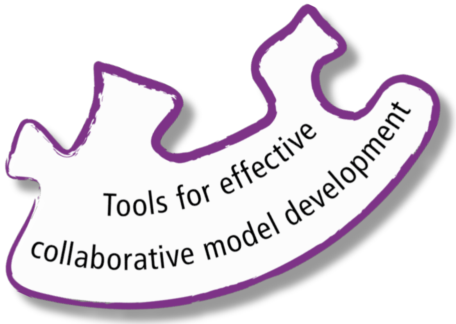
… by moving to "script-based" data processing & analysis

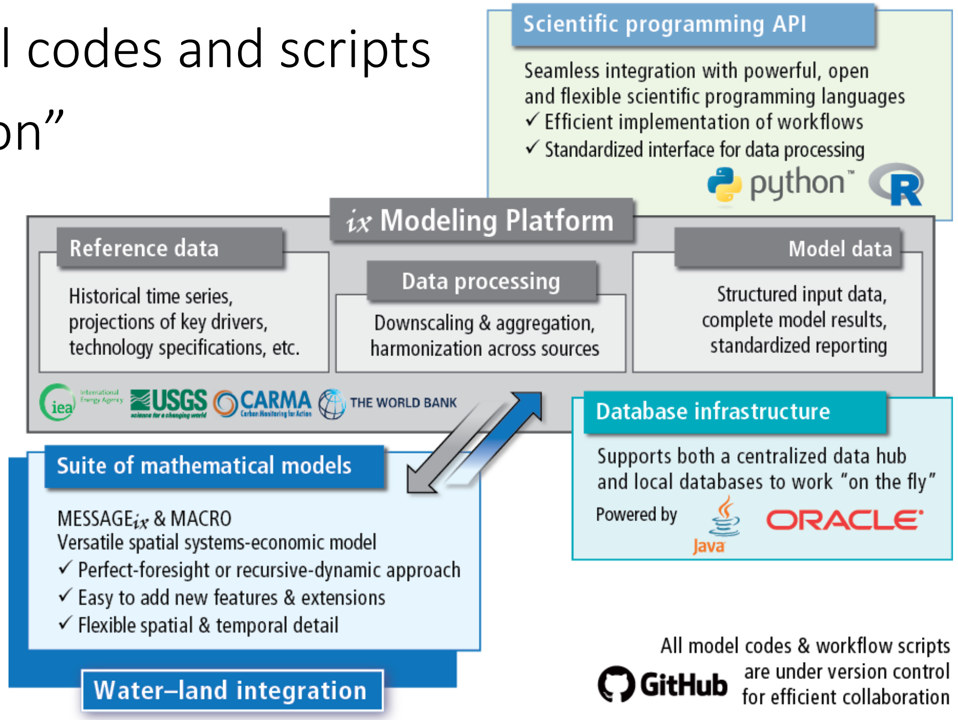
… using full version control of all model codes and scripts

… implementing "continuous integration"

⇒ automated testing of new features to ensure stable code base

GitHub





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python™ R

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Water–land integration

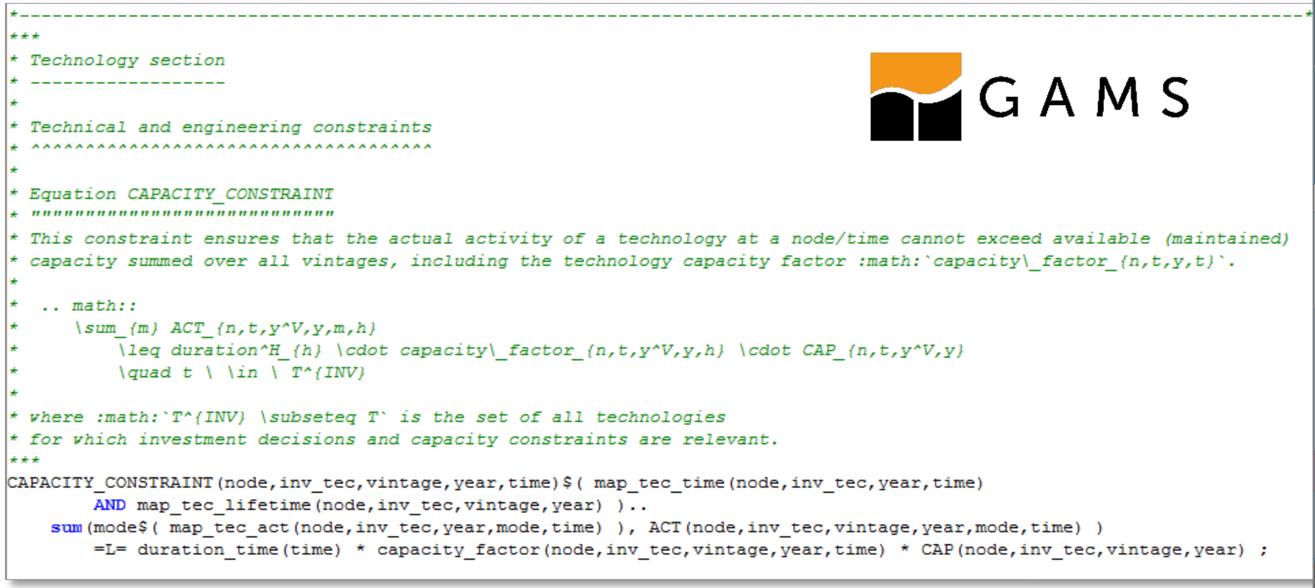
GitHub All model codes & workflow scripts are under version control for efficient collaboration

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

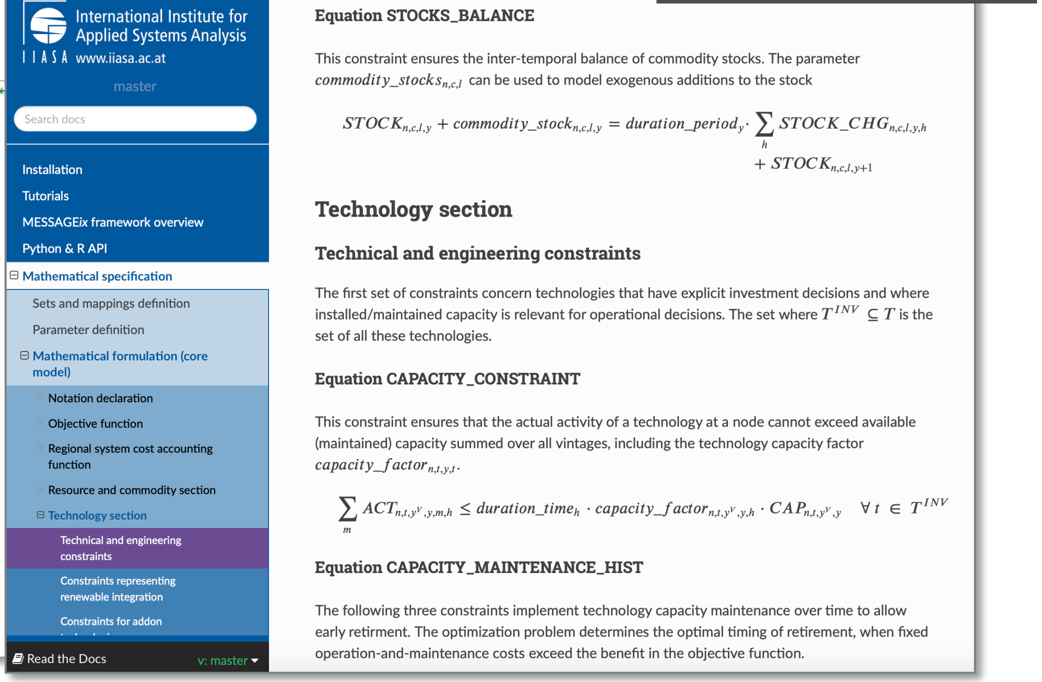
- ⇒ Documentation of all scientific programming packages using ‘sphinx‘
- ⇒ Documentation of the mathematical equations generated automatically from LaTeX mark-up in the GAMS code



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

Read the Docs

Scientific programming API



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

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

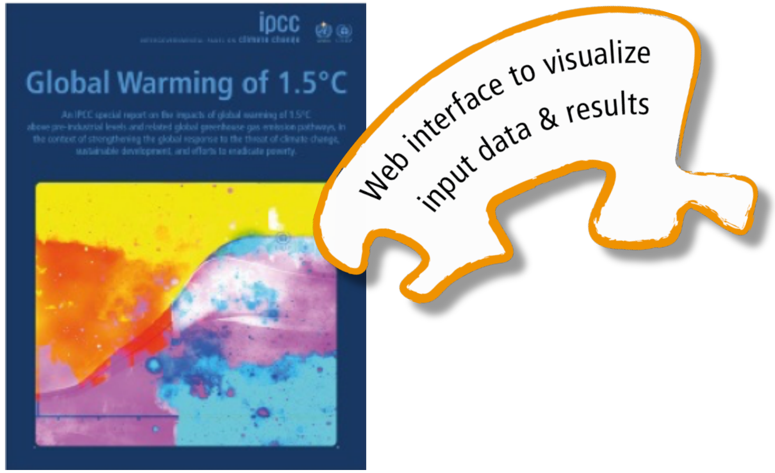
Equation CAPACITY_MAINTENANCE_HIST

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

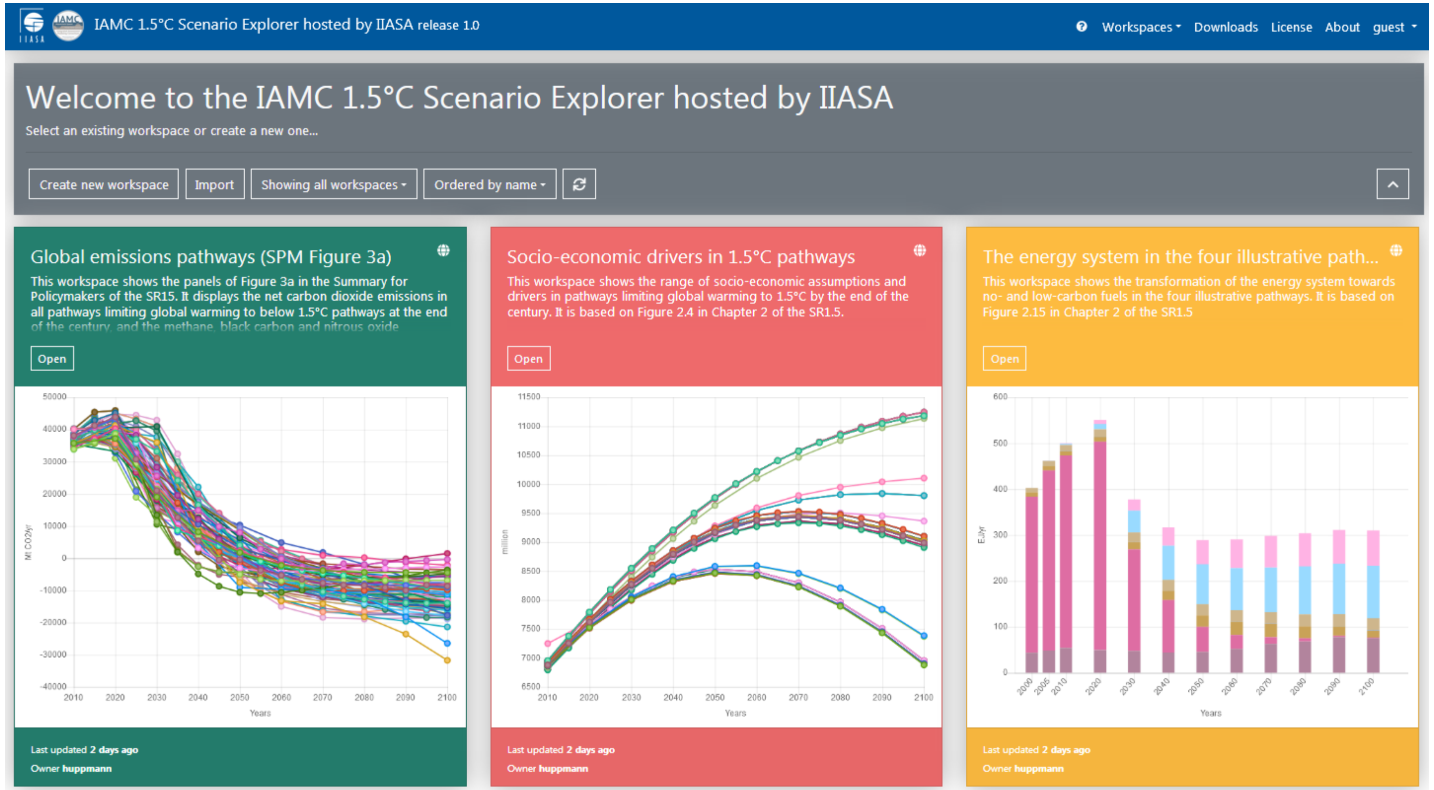
An intuitive gateway to modeling data for researchers and a wider audience

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



IAMC 1.5°C Scenario Explorer hosted by IIASA release 1.0

Welcome to the IAMC 1.5°C Scenario Explorer hosted by IIASA

Select an existing workspace or create a new one...

Global emissions pathways (SPM Figure 3a)

This workspace shows the panels of Figure 3a in the Summary for Policymakers of the SR15. It displays the net carbon dioxide emissions in all pathways limiting global warming to below 1.5°C pathways at the end of the century, and the methane, black carbon and nitrous oxide

Last updated 2 days ago
Owner huppmann

Socio-economic drivers in 1.5°C pathways

This workspace shows the range of socio-economic assumptions and drivers in pathways limiting global warming to 1.5°C by the end of the century. It is based on Figure 2.4 in Chapter 2 of the SR1.5.

Last updated 2 days ago
Owner huppmann

The energy system in the four illustrative path...

This workspace shows the transformation of the energy system towards no- and low-carbon fuels in the four illustrative pathways. It is based on Figure 2.15 in Chapter 2 of the SR1.5

Last updated 2 days ago
Owner huppmann

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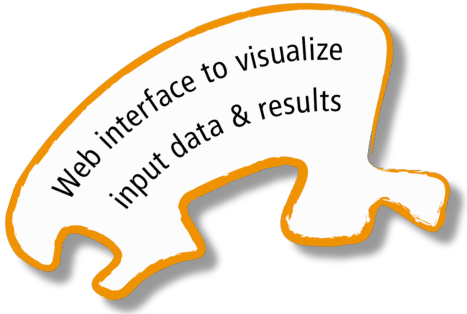

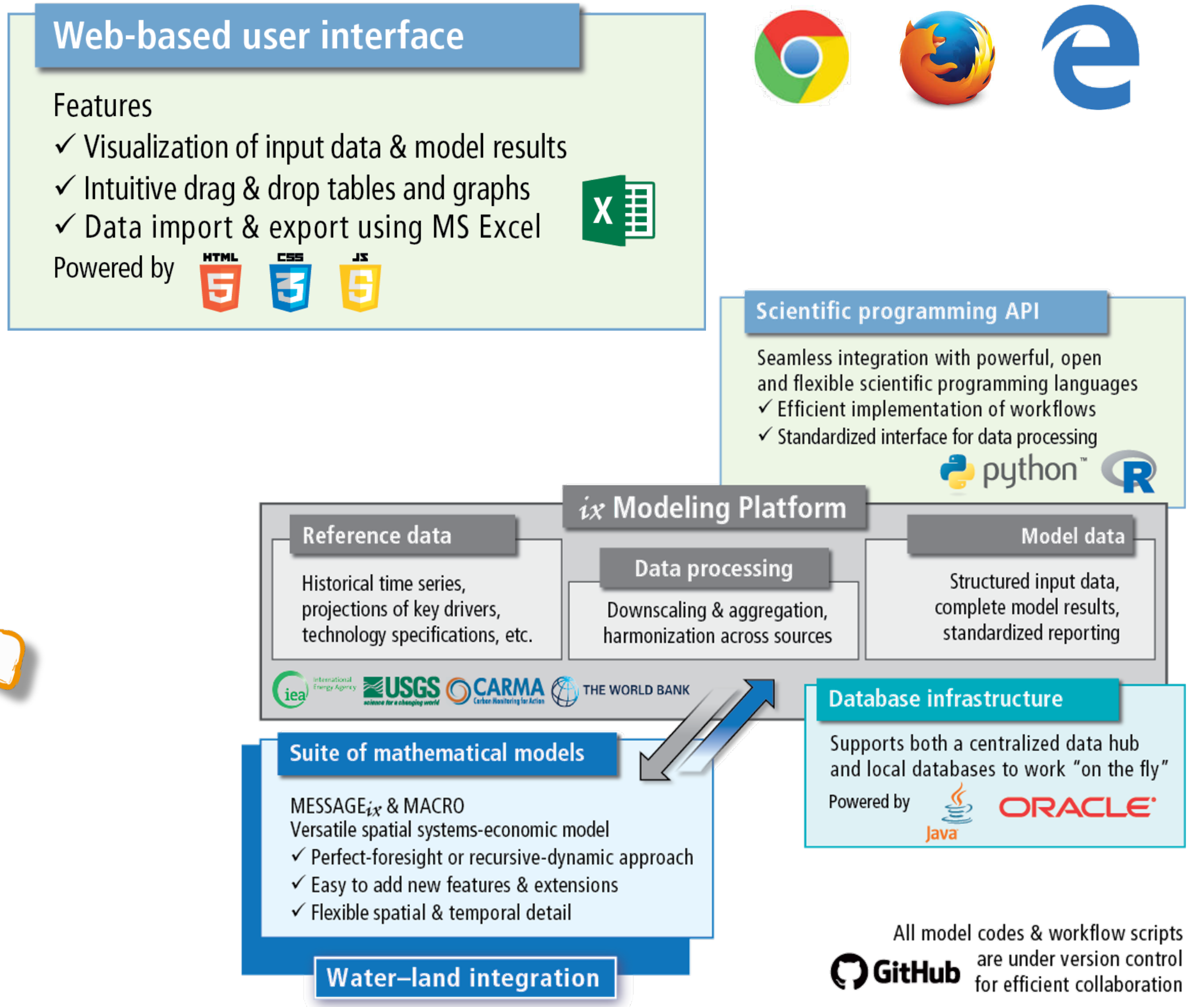

Web-based user interface

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

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python™ R

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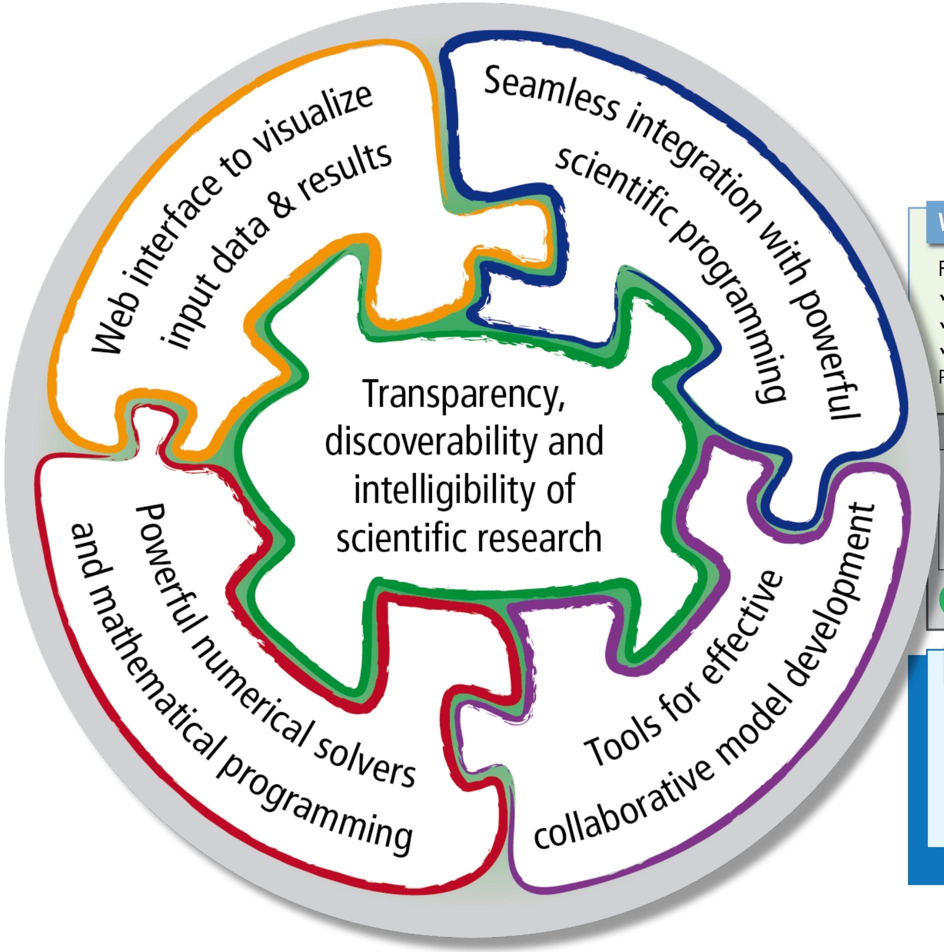
Water–land integration

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

The MESSAGE$_{ix}$ framework

Facilitating transparency and reproducibility of research



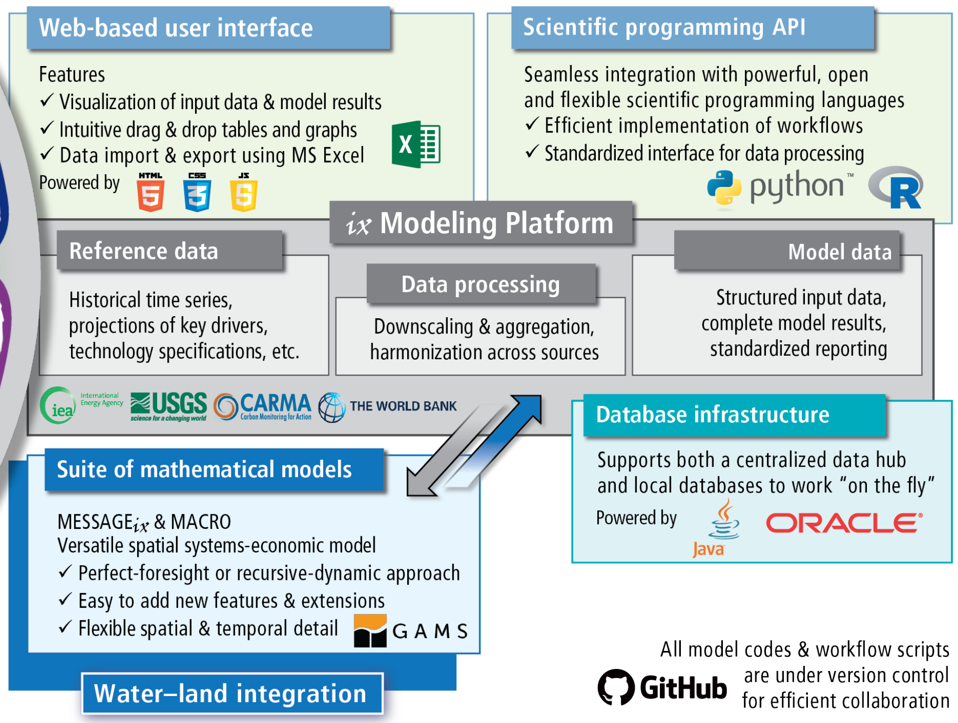
Web interface to visualize input data & results

Seamless integration with powerful scientific programming

Transparency, discoverability and intelligibility of scientific research

Powerful numerical solvers and mathematical programming

Tools for effective collaborative model development



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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
```

Important install issue:

⇒ We use the Python package to manage communication between the Java core and Python, but there is a conflict with recent versions – so you need to install v0.7.1 manually

```
$ conda install JPype==0.7.1
```

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”

GAME OF THRONES

Homework assignment

Let there be light in Westeros

Create new notebook(s) starting with a clone of a MESSAGEix Westeros tutorial scenario.

- 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 and gas are used at the same time?

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

Thank you very much for your attention!

Dr. Daniel Huppmann

Research Scholar – Energy Program

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