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# The Global Energy System Model (GENeSYS-MOD) v4.0 - A Flexible Energy System Modelling Framework for Julia and GAMS

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## Summary

GENeSYS-MOD is a flexible framework that allows the modelling of energy systems at various degrees of detail, with a focus on sector coupling and the computation of long-term pathways for the energy system. The generic formulation makes the framework suitable for a wide range of use cases, allowing for a widely user-defined resolution in terms of temporal, spatial, and technological detail. GENeSYS-MOD performs a cost-optimizing investment and dispatch calculation across all modeled subsectors of the energy system (usually covering at least electricity, buildings, industry, and transport). The newest, fourth version of the framework is now available in both GAMS and Julia for the core model, with optional data management tools written in Python.

## Statement of need

Energy system models are powerful tools commonly used to create detailed insights into possible future developments of the energy system, providing valuable information to decision makers. This includes a variety of model outputs such as cost-efficient capacity planning for both generation and flexibility options, as well as information on the resulting costs, supply mixes, and emission trajectories. Noteworthy examples of other established open energy system modelling frameworks include PyPSA (Brown et al., 2018), OSeMOSYS (Howells et al., 2011), oemof (Hilpert et al., 2018), Balmorel (Wiese et al., 2018), TIMES (Loulou et al., 2005), or EMPIRE (Backe et al., 2022). A comparison of several open source energy system modelling frameworks, including GENeSYS-MOD can be found at Candas et al. (2022) .

GENeSYS-MOD, which stands for "The Global Energy System Model", was originally released in 2017 (Löffler et al., 2017) and has since then been updated and expanded several times. However, one major shortcoming of older GENeSYS-MOD versions was that it was only available for the General Algebraic Modeling Language (GAMS), a commercial software for model building, which restricted the openness of the framework. Therefore, with version 4.0, we now introduce a new Julia version of GENeSYS-MOD that offers the exact same functionality as the GAMS-based version, but removes all commercial license requirements, especially when also using an open solver such as HiGHS.

## Overview over the functionality and capabilities of GENeSYS-MOD

GENeSYS-MOD is a cost-optimizing linear program that computes cost-optimal pathways for the energy system across multiple sectors, usually focusing on long-term pathways for the energy system. Figure 1 shows some of the core inputs and outputs of the model. Contrary to what the name suggests, GENeSYS-MOD can not only be applied at the global level (even though that was the initial application (Löffler et al., 2017)), but instead is purely driven by the underlying input data and has been successfully used in both macro-regional (e.g. Europe) (Moskalenko et al., 2024), country-level (Hanto et al., 2021), and even regional levels (Herpich et al., 2024).

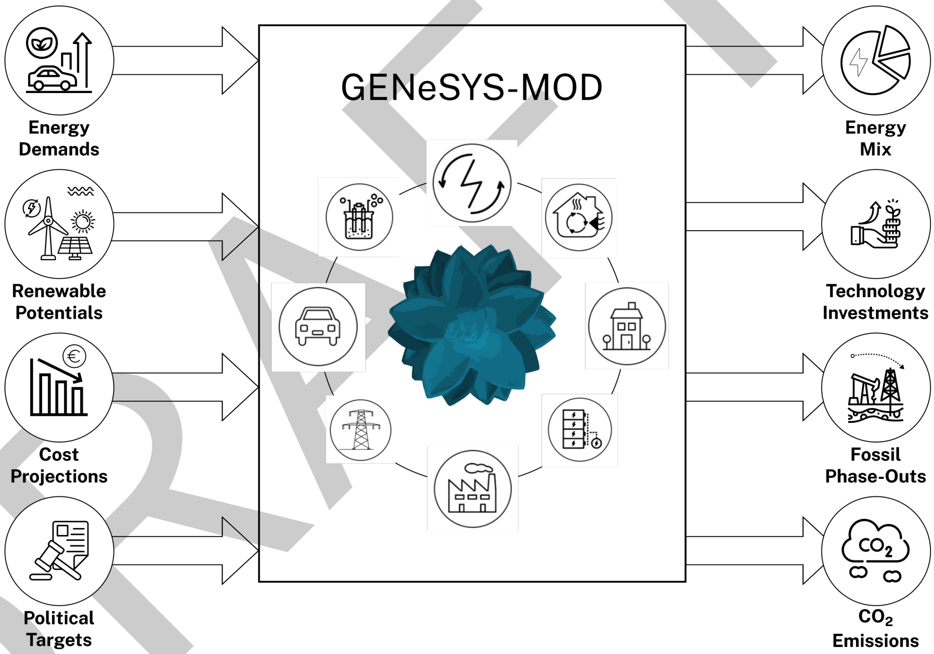


**Figure 1:** Main inputs and outputs of GENeSYS-MOD.

## Methodological background

In its origin, GENeSYS-MOD is based on the Open Source Energy Modelling System (OSeMOSYS), but has been altered and expanded in functionality over time. Nevertheless, the overall structure and nomenclature have been kept as measures to make the model easy to learn and use. GENeSYS-MOD optimizes the investment decisions on an annual level for a defined model period, usually given in five-year steps towards 2050 or 2060. To do so, it starts with an existing system setup based on historic data (brown-field approach). It then assumes a planner's perspective with perfect foresight as the default option, however, a myopic approach can also be chosen. The time resolution within a year can be flexibly defined via a timeseries reduction algorithm following Gerbaulet & Lorenz (2017). This means that depending on the user's computational resources and model setup, almost any time resolution, up to full hourly operation, can be chosen.

## General framework structure of GENeSYS-MOD version 4

The overall ecosystem of GENeSYS-MOD has been growing over time and now includes a multitude of features not only within, but also in conjunction with the core modelling framework. Figure 2 displays a graphic representation of the different repositories and features.

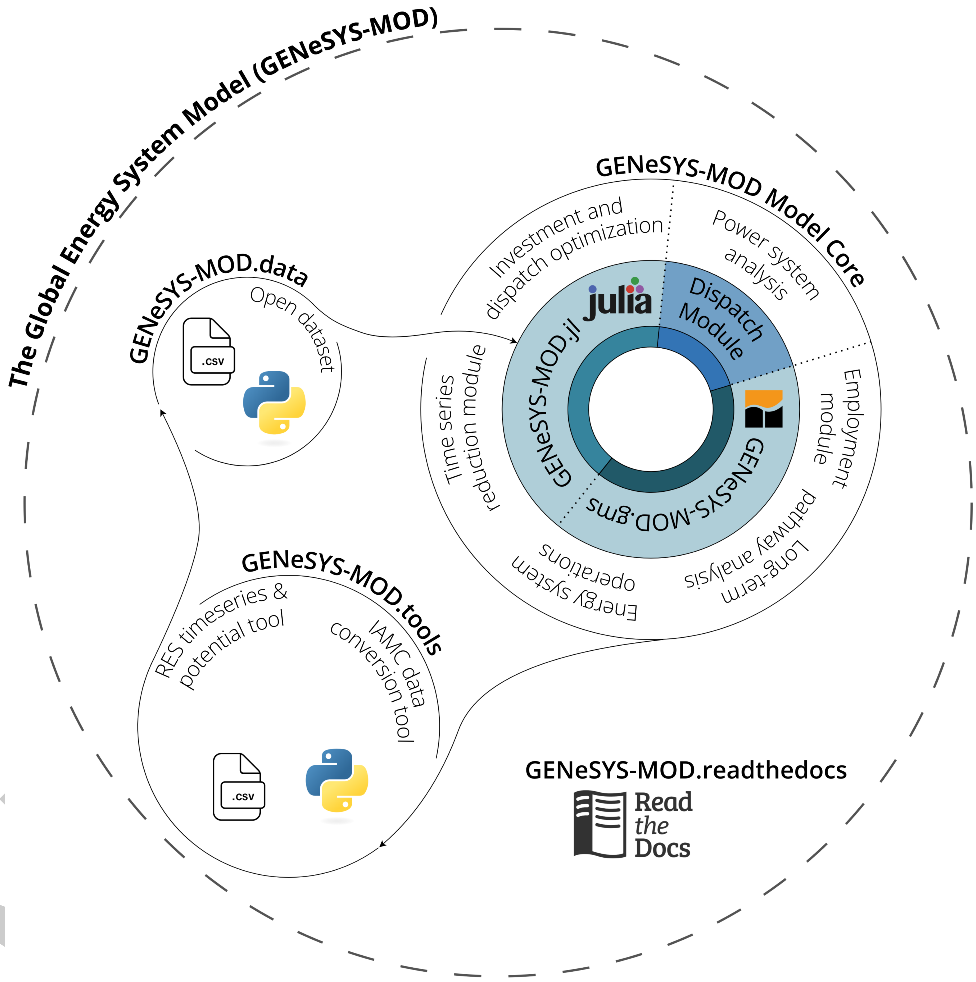


**Figure 2:** Ecosystem of GENeSYS-MOD v4.

## GENeSYS-MOD.data

The GENeSYS-MOD.data repository contains all the individual input parameters for building models, stored in csv files. Python-based scripts enable a filtering, aggregation, and disaggregation of the data. The scripts then return standardized input files for the core model. Users can also directly download finished input data files, thus use of these features is optional.

## GENeSYS-MOD core model

The core model source code of GENeSYS-MOD is available in both GAMS and Julia, with both versions being maintained side by side. The model also features a full hourly dispatch module, aimed at evaluating the electricity supply configuration that GENeSYS-MOD has provided.

## GENeSYS-MOD.tools

At this current time, two tools are provided: one focused on generating renewable timeseries and capacity potentials, making use of the open source Atlite package (Hofmann et al., 2021), as well as one conversion script, allowing GENeSYS-MOD datasets to be converted into the IAMC nomenclature (see here).

## Documentation

Encompassing all the other tools and the core model, the documentation is now provided via a readthedocs page that is continuously expanded. Also, there are additional resources in the form of video tutorials uploaded to a YouTube channel.

# New features of GENeSYS-MOD version 4

Figure 3 displays the additions across multiple major versions of GENeSYS-MOD.

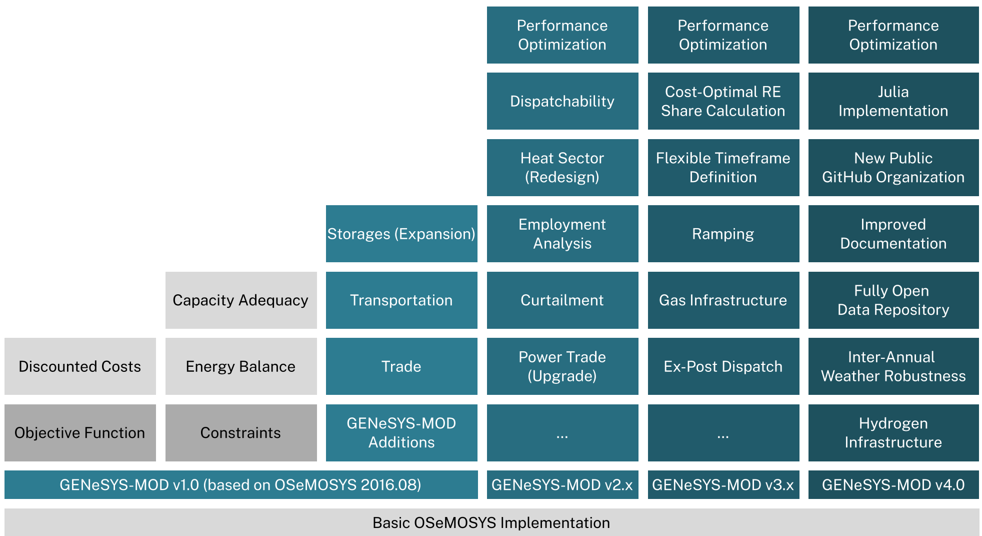


**Figure 3:** Functionality additions of major GENeSYS-MOD versions.

With version 4.0, the main focus was on the removal of entry barriers (in the form of commercial license requirements), improving data transparency, and making the framework easier to use. This has been tackled by various additions: 1. **Creation of a new GitHub organization:** previously, development of GENeSYS-MOD happened at a closed GitLab instance, hosted by TU Berlin, with one public repository that faced outwards. With the new structure, all development now happens in the new public GitHub repositories. 2. **Implementation of GENeSYS-MOD in Julia:** as stated above, GENeSYS-MOD used to be only available in GAMS, requiring a license which provides a cost barrier to prospective users. By offering a Julia implementation, the model can be used by a wider audience without any entry barriers. 3. **Fully open data repository:** in the past, completed data sets, usually accompanying a publication, would be uploaded to Zenodo. Now, instead, all raw input data is stored in a public repository, including individual sources of all data points, making the data more transparent and easier to use for other (e.g. regional) applications. The repository also comes with useful scripts for filtering and aggregation methods. 4. **A new and improved documentation:** the old documentation in the form of multiple PDF files has been replaced by a readthedocs page which serves as a wiki for everything related to the model and its tools. The nature of the readthedocs being hosted in a public GitHub repository also allows for easier and thus more collaboration on the documentation side. 5. **Performance optimization and new modelling features:** last but not least, several improvements to the model source code have been performed, significantly improving the performance for higher time resolutions. Also, new features regarding e.g. the repurposing of natural gas infrastructure to hydrogen or the blending of hydrogen in natural gas grids have been introduced.

## Past and ongoing research applications

GENeSYS-MOD has been used in a wide range of academic publications and research projects with several different regional focus points and research questions. Examples past the original global application (Löffler et al., 2017) include a multitude of analyses on the European continent, e.g. on the topic of asset stranding (Löffler et al., 2019), the phase out of Russian fossil fuel imports (Moskalenko et al., 2024), or the repurposing of the natural gas infrastructure for hydrogen applications (Hanto et al., 2024), but also a number of country-level case studies on India (Lawrenz et al., 2018), Germany (Bartholdsen et al., 2019), China (Burandt et al., 2019), Mexico (Sarmiento et al., 2019), South Africa (Hanto et al., 2021), or Japan (Burandt, 2021). GENeSYS-MOD has also been part of the model experiment (MODEX) project open_MODEX, where five open energy system modelling frameworks have been compared with each other, giving an overview in the respective strengths of the different frameworks (Berendes et al., 2022; Candas et al., 2022; Ouwerkerk et al., 2022). Also, noteworthy research projects include the Open ENTRANCE project (see here), iDesignRES (see here), Man0EUvRE (see here) or OpenMod4Africa (see here).

## Perspective

The software and its ecosystem are under constant development and always looking to improve, be it in terms of functionalities, accessibility, or new exciting research opportunities. Therefore, a small community has established itself, with regular online meetings and an annual development workshop. The goal would be to follow great pioneers like the OSeMOSYS community in that regard, like described in Gardumi et al. (2018).

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