AnyMOD.jl: A Julia package for creating energy system models

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Abstract

AnyMOD.jl is a Julia framework for creating large-scale energy system models with multiple periods of capacity expansion. It applies a novel graph-based approach that was developed to address the challenges in modeling high levels of intermittent generation and sectoral integration. Created models are formulated as linear optimization problems using JuMP.jl as a backend.

To enable modelers to work more efficiently, the framework provides additional features that help to visualize results, streamline the read-in of input data, and rescale optimization problems to increase solver performance.

Keywords: Macro-energy systems, Energy system modeling, Open-source modeling, Julia
1. Motivation and significance

Since the production of energy accounts for three-quarters of global emissions, mitigating climate change requires the decarbonization of the energy system [1]. Cutting emissions requires to shift supply of primary energy to electricity from wind and solar and extend its use to other sectors. As a result, the energy system has to undergo fundamental change and evolve from largely independent sectors with little supply from renewables into an integrated system characterized by fluctuating renewables.

Capacity expansion models investigate the long-term developments of macro-energy systems, but existing methods were developed for systems still characterized by fossil fuels and struggle to describe the transformation towards a renewable system [2]. Models like ReEDS, Message, or Switch, pursue a time-slice approach, that reduces the entire year to a small number of independent periods [3, 4, 5]. This reduction limits the detail applied to fluctuating renewables and more importantly prohibits to consider long-term storage, a key component of renewable energy systems [6, 7]. Other models, like PyPSA or Calliope, diverge from this approach and consider a continuous and hourly time-series instead, which enables a detailed representation of renewables and long-term storage [8, 9]. But in return these models are
limited to a single year and, opposed to models using time-slices, cannot
analyze development pathways for today’s system.

Against this background, AnyMOD.jl provides a framework for modeling
the long-term transformation of the energy system with the level of detail
necessary to represent fluctuating renewables and long-term storage. The
framework implements a novel graph-based method introduced in Göke [10]
that varies the level of temporal and spatial detail by energy carrier to keep
models with high resolution computationally tractable. The approach also
enables to model the substitution of energy carriers and, on the practical
side, facilitates the read-in of input data.

AnyMOD.jl follows an easy to use, but difficult to master principle. Since
individual models are solely defined by CSV files and can be run with a few
lines of standard code, running an existing model, and performing sensitivity
analysis requires little experience. More advanced applications, like creat-
ing new models and individually modifying their formulation, requires some
programming skills and a deeper understanding of the framework’s structure.
Since models are defined from CSV files and short code scripts, the framework
supports version-controlled model development to promote collaboration and
transparency.

The following section gives an overview of the framework’s structure and
presents two functionalities with greater detail, the read-in of parameter data
(section 2.2.1) and the re-scaling algorithm (section 2.2.2). The subsequent
section describes an application that models the transformation of the Euro-
pean power and gas sector. The final section paper highlights the framework’s
impact and concludes.

2. Software description

The package is implemented in Julia. Its key dependencies are JuMP.jl
as a backend for linear optimization and DataFrames.jl for data processing
[11, 12]. The framework uses PyCall.jl to create an internal Python envi-
ronment and apply the Python packages NetworkX and Plotly for plotting.
Gurobi is added as an optional dependency, because its function to compute
irreducible inconsistent subsystems is utilized to debug infeasible models.
Apart from that, the framework is compatible with any open or commercial
solver implemented in Julia. To increase performance the package heavily
utilizes Julia’s multi-threading capabilities. Since not supported by JuMP.jl,
the mere creation of constraints uses only one thread, but the computationally
more intensive composition of constraints from variables and parameters
is multi-threaded.
2.1. Software Architecture

The class diagram in Figure 1 illustrates the architecture of AnyMOD.jl and how it revolves around the AnyModel object. For the sake of clarity, the diagram is not exhaustive and only covers the most relevant dependencies, objects and attributes. Listing 2.1 provides the corresponding code to initialize, populate, solve and analyze the model object.

After loading AnyMOD.jl, the constructor initializes the AnyModel object based on two mandatory arguments: an input directory and an output directory. The CSV files defining a model consist of set and parameter files that have to be placed in the input directory. The set files define all time-steps, regions, energy carriers and technologies considered in a model and map how these are related, for example which carriers a technology can generate. Following the graph-based approach, the elements of each set are organized as nodes of hierarchical trees.

```plaintext
using AnyMOD # loading packages
model_object = anyModel("..\demo","results") # construct model object

# create optimization problem and set an objective
createOptModel!(model_object)
setObjective!(:costs, model_object)

# solve model and report results
```

Figure 1: UML class diagram of package components
Table 2: Exemplary data frame of generation variables

| time-step | region | carrier | technology | variable   |
|-----------|--------|---------|------------|------------|
| 1         | 1      | 1       | 1          | gen(1,1,1,1) |
| 2         | 1      | 1       | 1          | gen(2,1,1,1) |
| 3         | 1      | 1       | 1          | gen(3,1,1,1) |

Listing 1: Script to initialize, create and run a model

```plaintext
using Cbc
set_optimizer(model_object.optModel, Cbc.Optimizer)
optimize!(model_object.optModel)
reportResults(:summary, model_object)
```

Qualitative inputs on sets are complemented with quantitative data from the parameter files, that for instance provide demand time-series or technology properties like investment costs or efficiency. While the naming and format of set files is strictly defined, parameter data can be freely structured and distributed across files. As a result, models can be composed modularly, since different models can share the same input files. After reading in all parameter data, the constructor creates a `ParElement` object for each parameter with data and meta information and assigns it to a `ModelPart` object. The `ModelPart` objects partition the model into different parts, for instance, the `ParElement` for demand time-series will be assigned to a model part dedicated to the energy balance. Each technology got its own part object of the subclass `TechPart`, that also stores technology specific attributes like assigned carriers.

After construction, the `AnyModel` object is passed to the `createModel!` function, which creates all the variables and constraints of the underlying optimization problem `optModel`. These variables and constraints are again assigned to model parts and stored as data frames. For instance, Table 2 depicts a data frame of generation variables. The column on the right stores the JuMP variable objects and the four other columns give the time-step, region, carrier, and technology of each variable, which are provided as indexes of the `Node` objects created during initialization. Such data frames for variables are combined with parameter data using database operations to construct constraints. For instance, generation variables are aggregated by technology and then joined with the demand parameter to create the energy balance in Table 3.

After the optimization problem is created, its objective is set with the `setObjective` function. At this point the user can also freely modify and extend the automatically generated problem by accessing the JuMP attributes of the
| time-step | region | carrier | constraint |
|-----------|--------|---------|------------|
| 1         | 1      | 1       | $dem(1, 1, 1) = \sum_t gen(1, 1, 1, t)$ |
| 2         | 1      | 1       | $dem(2, 1, 1) = \sum_t gen(2, 1, 1, t)$ |
| 3         | 1      | 1       | $dem(3, 1, 1) = \sum_t gen(3, 1, 1, t)$ |

Table 3: Exemplary data frame of energy balance constraints

AnyModel object and its parts. Finally, the optimization problem optModel is passed to a solver and analyzed afterwards. All results are written to the output directory, which was passed to the constructor in the beginning. A reporting file with error messages and warnings is written to this directory as well.

2.2. Software Functionalities

As outlined above, AnyMOD.jl is a package for the creation of energy system models. Additional features are aimed either at simplifying its application or enhancing the performance of creating and solving models. In the following, two of these features are presented in greater detail.

2.2.1. Inheritance Algorithm

As explained above, model constraints are constructed from variables and parameters, which are again defined by input data. Usually, models use a single parameter value in many constraints. For example, the efficiency of a newly build gas power plant does typically not vary by time-step or region and all constraints describing these plants will use the same value. Consequently, it would be inefficient, if AnyMOD.jl required users to provide efficiency data at a temporal and spatial resolution. On the other hand, efficiencies of heat-pumps are highly dependant on region and time-step, because they depend on ambient temperature. So, not permitting efficiencies to depend on time-step and region, would prevent to model these technologies accurately.

A similar problem occurs, if investment costs of emerging technologies, like photovoltaic, are expected to decrease within the model horizon, but costs for other technologies remain constant. Here, providing all costs at a yearly resolution leads to redundant inputs for most technologies, but if costs cannot be varied by year at all, cost degression of photovoltaic cannot be modelled. In conclusion a predefined resolution of input data either results in an highly inefficient read-in of input data or restricts modelling capabilities.

To resolve this problem, AnyMOD.jl does not predefine the resolution of input data and instead automatically infers how data should be used from the way it is specified. For example, providing different efficiencies in dependence of time-step and region will result in temporally and spatially resolved
efficiencies in the model, but if instead a parameter is provided without
time-steps or regions, the model uses a uniform value. This concept is not
limited to certain parameters or dimensions, but applies comprehensively.
The implementing algorithm builds on the idea to "inherit" missing data for
a specific node from its relatives in the hierarchical tree.¹

Figure 2 illustrates the basic mechanism of the algorithm based on an
exemplary hierarchical tree organizing time-steps. The first level of the tree
organizes different years with days, 4-hours steps and hours following on the
subsequent levels. Green numbers indicate input data provided for a specific
node. If input data is not specified in dependence of the time-step, it is
assigned to the root of the tree. The algorithm can obtain missing data at
the circled node in three different ways: either move up the tree and use ‘8.3’,
move down the tree and sum the hourly values, or move down the tree and
average the hourly values. How the algorithm deploys these three methods
for each dimension depends on the inheritance rules of the parameter. A
detailed overview for each parameter is provided in the parameter list of the
documentation.

Figure 3 outlines how these rules then are deployed to obtain parame-
ter data. The described algorithm corresponds to the matchSetParameter
function of ParElement in Figure 1 and takes the following inputs: a data

¹This idea of "inheritance" is not be confused with inheritance in the context of object
orientated programming.
frame to be filled with parameter data, a respective parameter object and
the hierarchical trees. First, the algorithm checks for direct matches between
the input data frame and the parameter data. Afterwards, it loops over the
inheritance rules to inherit new data for missing nodes as described above. If
new data is obtained, the algorithm checks again for matches with the input
data frame. The loops ends when either all rows are matched with data, or all
inheritance rules have been applied. In the latter case, unassigned rows are
either dropped or assigned a default value, if one is defined for the respective
parameter.

| **Input:** | data frame requiring data, parameter object, hierarchical
trees |
| **Output:** | data frame with parameters assigned |
| find matches of data frame with parameter data; |
| for I do |
| try to inherit new data for missing nodes; |
| if new data obtained then |
| add newly obtained data to parameter object; |
| find new matches of data frame and parameter data; |
| if no unmatched rows in data frame anymore then |
| exit loop; |
| end |
| end |
| if parameter has default value then |
| use default for unmatched rows; |
| else |
| drop unmatched rows; |
| end |

Figure 3: Inheritance algorithm

2.2.2. Scaling
The formulation of an optimization problem can have a major impact on
solver performance. The barrier algorithm, the fastest method for solving
large linear problems, is particularly sensitive to a model’s numerical prop-
erties, and poor formulations will thus greatly increase computation time.
For this reason, AnyMOD.jl automatically applies a two-step scaling pro-
cess when creating optimization problems. The process aims to narrow the
range of coefficients and constants in a problem between $10^{-3}$ and $10^6$, as recommended.

As a demonstration of how this range is achieved, Eq. 1 constitutes the constraints of an exemplary linear model. In the first and second row, the coefficients for $x_1$ are currently outside of the targeted interval. In addition, the maximum range of coefficients in the second row amounts to $10^{11}$ ($= 10^2 - 9$), which exceeds the maximum range of the targeted interval of $10^9$ ($= 10^6 - 3$) and means the equation cannot be multiplied with a constant factor to shift coefficients into the desired interval.

$$
\begin{align*}
10^{-8} x_1 + 10^3 x_2 + x_3 & \leq b_1 \\
10^{-9} x_1 + 10^2 x_2 + x_3 & \leq b_2 \\
10^{-8} x_1 + 10^3 x_2 + x_3 & \leq b_2
\end{align*}
$$

Therefore, in the first step the maximum range of coefficients is decreased by substituting variables. In the example, $x_1$ is substituted with $10^3 x'_1$, which results in the system displayed in Eq. 2.

$$
\begin{align*}
10^{-5} x'_1 + 10^3 x_2 + x_3 & \leq b_1 \\
10^{-6} x'_1 + 10^2 x_2 + x_3 & \leq b_2 \\
10^3 x'_1 + 10^2 x_2 + x_3 & \leq b_2
\end{align*}
$$

Since the first step decreased the maximum range, in the second step coefficients can be shifted into the interval between $10^{-3}$ and $10^6$. For this purpose, each constraint (or row) is scaled with a constant factor. In the example, the first row is multiplied by $10^2$ and the second row by $10^3$ resulting in the system displayed in Eq. 3 that finally complies with the recommended range.

$$
\begin{align*}
10^{-3} x'_1 + 10^5 x_2 + 10^2 x_3 & \leq 10^2 b_1 \\
10^{-3} x'_1 + 10^5 x_2 + 10^3 x_3 & \leq 10^3 b_2 \\
10^3 x'_1 + 10^5 x_2 + 10^3 x_3 & \leq b_2
\end{align*}
$$

AnyMOD.jl uses default factors for substitution that depend on the variable type and can be adjusted if they fail to achieve the desired result. Factors for scaling can be automatically computed based on the current coefficients in a constraint.

Figure 4 demonstrates the impact of automated scaling by comparing the solve times of Gurobi’s barrier implementation for a test model.\textsuperscript{3} To

\textsuperscript{2}See the Gurobi Guidelines for Numerical Issues for details.
\textsuperscript{3}The corresponding model files can be found in the following repository: https://github.com/leonardgoeke/AnyMOD_example_model/tree/May2020
ensure robustness of the results, Barrier was run with both available ordering algorithms, “approximate minimum degree” and “nested dissection.” With automated scaling disabled, a \textit{NumericFocus} parameter of three is necessary to avoid early termination or extremely long solve times due to numerical difficulties. In conclusion, automated scaling decreases solve time of the test model roughly by a factor of three.

3. Illustrative Example

Hainsch et al. [13] applied AnyMOD.jl to the decarbonization of the European power and gas sector on a pathway from 2030 to 2040 instead of a single year. The analysis with AnyMOD.jl complements results from another energy system model with less spatiotemporal detail. The application subdivides Europe on a country level and includes an aggregated representation of transmission infrastructure to enable the exchange of energy carriers between countries.

Figure 5 was plotted with the \texttt{plotEnergyFlow} function and provides an overview of the technologies and energy carriers considered. In the graph, carriers are symbolized by colored vertices and technologies by gray vertices. Entering edges of technologies point towards their input carriers; outgoing edges refer to outputs. Since the model includes both the power and gas sector, it is not limited to short-term storage of power, like batteries, but also considers creation and utilization of synthetic fuels for long-term storage. Since fluctuating renewables are the main source of supply by 2040, power is modelled at an hourly resolution. To reduce model size and account for the inherent flexibility of gaseous energy carriers, fossil gas, hydrogen,
and synthetic gas are balanced daily instead. All other energy carriers are modelled yearly.

The energy flows for France in 2040 when solving the model are displayed in Figure 6. The sankey diagram does not only show how hydrogen is used for long-term storage of power, but also how final demand for hydrogen and synthetic gases, for example from the industry sector, is covered. In addition, the substantial amount of imports and exports for all carriers highlights the importance of large models that can account for several regions at once.
4. Impact and conclusions

AnyMOD.jl provides a framework for modeling the transformation towards a decarbonized energy system at a high spatiotemporal resolution. For this purpose, it implements a graph-based method introduced that enables to vary the level of detail by energy carrier. In addition, the framework introduces a more flexible method to read-in input data and automatically scales created optimization problems to increase solver performance. Lastly, the tool provides advanced plotting features, like Sankey diagrams.

To facilitate access for users, AnyMOD.jl can be used without any proprietary software. Using the framework does not require extensive programming skills but supports version-controlled model development, since models are created from CSV files. To extend and modify a created model, advanced users can easily access and manipulate its underlying JuMP objects. The organization of input files is highly flexible and eases the creation of new models from existing files.

In conclusion, AnyMOD.jl enables research to spend less time on coding and data management and more time focusing on the scientific part of their work. Its high level of accessibility also makes AnyMOD.jl suitable for use by companies, regulators, or non-governmental organizations. Finally, AnyMOD.jl promotes openness and transparency in various ways. Due to the relevance of these qualities for public policy, this is of particular importance with energy system models [14].

Additional features currently developed include a more detailed representation of transmission infrastructure and the inclusion of more than one
weather year in a single model. The later also includes the development of a distributed solution algorithm to keep the resulting increase in model size manageable.

5. Conflict of Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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References

[1] O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, J. Minx, Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.

[2] P. Levi, S. Kurland, M. Carbajales-Dale, J. Weyant, A.-R. Brandt, S. Benson, Macro-energy systems: Toward a new discipline, Joule 3 (2019) 2282–2286. doi:https://doi.org/10.1016/j.joule.2019.07.017.

[3] S. M. Cohen, J. Becker, D. A. Bielen, M. Brown, W. J. Cole, K. P. Eurek, A. Frazier, B. A. Frew, P. J. Gagnon, J. L. Ho, P. Jadun, T. T. Mai, M. Mowers, C. Murphy, A. Reimers, J. Richards, N. Ryan, E. Spyrou, D. C. Steinberg, Y. Sun, N. M. Vincent, M. Zwerling, Regional energy deployment system (reeds) model documentation: Version 2018 (2019). URL: https://www.osti.gov/biblio/1505935. doi:10.2172/1505935.
[4] M. Howells, H. Rogner, N. Strachan, C. Heaps, H. Huntington, S. Kypreos, A. Hughes, S. Silveira, J. DeCarolis, M. Bazillian, A. Roehrl, Osemosys: The open source energy modeling system: An introduction to its ethos, structure and development, Energy Policy 39(10) (2011) 5850–5870. doi:10.1016/j.enpol.2011.06.033.

[5] J. Johnston, R. Henriquez-Auba, B. Maluenda, M. Fripp, Switch 2.0: A modern platform for planning high-renewable power systems, Software X 10 (2019) 100251. doi:10.1016/j.softx.2019.100251.

[6] W. Schill, Electricity storage and the renewable energy transition, Joule 4 (2020) 2047–2064. doi:https://doi.org/10.1016/j.joule.2020.07.022.

[7] L. Göke, M. Kendziorski, The adequacy of time-series reduction for renewable energy systems, Working Paper (2021). URL: https://arxiv.org/abs/2101.06221.

[8] S. Pfenniger, B. Pickering, Calliope: a multi-scale energy systems modelling, Journal of Open Source Software 3(29) (2018) 825. doi:10.21105/joss.00825.

[9] T. Brown, J. Hörsch, D. Schlachtberger, PyPSA: Python for Power System Analysis, Journal of Open Research Software 6 (2018). URL: https://doi.org/10.5334/jors.188. doi:10.5334/jors.188.arXiv:1707.09913.

[10] L. Göke, A graph-based formulation for modeling macro-energy systems, Applied Energy 301 (2021) 117377. doi:10.1016/j.apenergy.2021.117377.

[11] I. Dunning, J. Huchette, M. Lubin, Jump: A modeling language for mathematical optimization, SIAM Review 59(2) (2017) 295–320. doi:https://doi.org/10.1137/15M1020575.

[12] J. Bezanson, A. Edelman, S. Karpinski, V. Shah, Julia: A fresh approach to numerical computing, SIAM Review 59(1) (2017) 65–98. doi:https://doi.org/10.1137/141000671.

[13] K. Hainsch, L. Göke, C. Kemfert, P.-Y. Oei, C. Hirschhausen, European green deal: Using ambitious climate targets and renewable energy to climb out of the economic crisis, DIW Weekly Report 28+29 (2020). doi:https://doi.org/10.18723/diw_dwr:2020-28-1.
Current executable software version

| Nr. | (Executable) software metadata description | Please fill in this column |
|-----|-------------------------------------------|---------------------------|
| S1  | Current software version                  | v0.1.6                     |
| S2  | Permanent link to executables of this version | `https://github.com/leonardgoeke/AnyMOD.jl/releases/tag/v0.1.6` |
| S3  | Legal Software License                     | MIT license (MIT)          |
| S4  | Computing platforms/Operating Systems      | Linux, Microsoft Windows, iOS |
| S5  | Installation requirements & dependencies  | Julia 1.3.1                |
| S6  | If available, link to user manual - if formally published include a reference to the publication in the reference list | `https://leonardgoeke.github.io/AnyMOD.jl/stable/` |
| S7  | Support email for questions                | `lqo@wip.tu-berlin.de`      |

Table 4: Software metadata