Calliope Documentation

Release 0.6.8

Calliope contributors

Feb 07, 2022

CONTENTS

v0.6.8 (*Release history*)

This is the documentation for version 0.6.8. See the main project website for contact details and other useful information.

Calliope focuses on flexibility, high spatial and temporal resolution, the ability to execute many runs based on the same base model, and a clear separation of framework (code) and model (data). Its primary focus is on planning energy systems at scales ranging from urban districts to entire continents. In an optional operational mode it can also test a pre-defined system under different operational conditions. Calliope's built-in tools allow interactive exploration of results:

A model based on Calliope consists of a collection of text files (in YAML and CSV formats) that define the technologies, locations and resource potentials. Calliope takes these files, constructs an optimisation problem, solves it, and reports results in the form of xarray Datasets which in turn can easily be converted into Pandas data structures, for easy analysis with Calliope's built-in tools or the standard Python data analysis stack.

Calliope is developed in the open on GitHub and contributions are very welcome (see the *Development guide*).

Key features of Calliope include:

- Model specification in an easy-to-read and machine-processable YAML format
- Generic technology definition allows modelling any mix of production, storage and consumption
- Resolved in space: define locations with individual resource potentials
- Resolved in time: read time series with arbitrary resolution
- Able to run on high-performance computing (HPC) clusters
- Uses a state-of-the-art Python toolchain based on Pyomo, xarray, and Pandas
- Freely available under the Apache 2.0 license

CHAPTER

ONE

USER GUIDE

1.1 Introduction

The basic process of modelling with Calliope is based on three steps:

1. Create a model from scratch or by adjusting an existing model (*Building a model*)
2. Run your model (*Running a model*)
3. Analyse and visualise model results (*Analysing a model*)

1.1.1 Energy system models

Energy system models allow analysts to form internally coherent scenarios of how energy is extracted, converted, transported, and used, and how these processes might change in the future. These models have been gaining renewed importance as methods to help navigate the climate policy-driven transformation of the energy system.

Calliope is an attempt to design an energy system model from the ground of up with specific design goals in mind (see below). Therefore, the model approach and data format layout may be different from approaches used in other models. The design of the nodes approach used in Calliope was influenced by the power nodes modelling framework by [Heussen2010], but Calliope is different from traditional power system modelling tools, and does not provide features such as power flow analysis.

Calliope was designed to address questions around the transition to renewable energy, so there are tools that are likely to be more suitable for other types of questions. In particular, the following related energy modelling systems are available under open source or free software licenses:

- SWITCH: A power system model focused on renewables integration, using multi-stage stochastic linear optimisation, as well as hourly resource potential and demand data. Written in the commercial AMPL language and GPL-licensed [Fripp2012].
- Temoa: An energy system model with multi-stage stochastic optimisation functionality which can be deployed to computing clusters, to address parametric uncertainty. Written in Python/Pyomo and AGPL-licensed [Hunter2013].
- OSeMOSYS: A simplified energy system model similar to the MARKAL/TIMES model families, which can be used as a stand-alone tool or integrated in the LEAP energy model. Written in GLPK, a free subset of the commercial AMPL language, and Apache 2.0-licensed [Howells2011].

Additional energy models that are partially or fully open can be found on the Open Energy Modelling Initiative's wiki.

1.1.2 Rationale

Calliope was designed with the following goals in mind:

- Designed from the ground up to analyze energy systems with high shares of renewable energy or other variable generation
- Formulated to allow arbitrary spatial and temporal resolution, and equipped with the necessary tools to deal with time series input data
- Allow easy separation of model code and data, and modular extensibility of model code
- Make models easily modifiable, archiveable and auditable (e.g. in a Git repository), by using well-defined and human-readable text formats
- Simplify the definition and deployment of large numbers of model runs to high-performance computing clusters
- Able to run stand-alone from the command-line, but also provide an API for programmatic access and embedding in larger analyses
- Be a first-class citizen of the Python world (installable with `conda` and `pip`, with properly documented and tested code that mostly conforms to PEP8)
- Have a free and open-source code base under a permissive license

1.1.3 Acknowledgments

Development has been partially funded by several grants throughout throughout the years. We would particularly like to acknowledge the following:

- The Grantham Institute at Imperial College London.
- the European Institute of Innovation & Technology's Climate-KIC program.
- Engineering and Physical Sciences Research Council, reference number: EP/L016095/1.
- The Swiss Competence Center for Energy Research Supply of Electricity (SCCER SoE), contract number 1155002546.
- Swiss Federal Office for Energy (SFOE), grant number SI/501768-01.
- European Research Council TRIPOD grant, grant agreement number 715132.
- The SENTINEL project of the European Union's Horizon 2020 research and innovation programme under grant agreement No 837089.

1.1.4 License

Calliope is released under the Apache 2.0 license, which is a permissive open-source license much like the MIT or BSD licenses. This means that Calliope can be incorporated in both commercial and non-commercial projects.

```
Copyright since 2013 Calliope contributors listed in AUTHORS

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you may not use this file except in compliance with the License.
You may obtain a copy of the License at

   http://www.apache.org/licenses/LICENSE-2.0
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```

1.1.5 References

1.1.6 Citing Calliope in academic literature

Calliope is published in the Journal of Open Source Software. We encourage you to use this academic reference.

1.2 Download and installation

1.2.1 Requirements

Calliope has been tested on Linux, macOS, and Windows.

Running Calliope requires four things:

1. The Python programming language, version 3.7 or higher.
2. A number of Python add-on modules (see *below for the complete list*).
3. A solver: Calliope has been tested with CBC, GLPK, Gurobi, and CPLEX. Any other solver that is compatible with Pyomo should also work.
4. The Calliope software itself.

1.2.2 Recommended installation method

The easiest way to get a working Calliope installation is to use the free `conda` package manager, which can install all of the four things described above in a single step.

To get `conda`, download and install the "Miniconda" distribution for your operating system (using the version for Python 3).

With Miniconda installed, you can create a new environment called `"calliope"` with all the necessary modules, including the free and open source GLPK solver, by running the following command in a terminal or command-line window

```
$ conda create -c conda-forge -n calliope calliope
```

To use Calliope, you need to activate the `calliope` environment each time

```
$ conda activate calliope
```

You are now ready to use Calliope together with the free and open source GLPK solver. However, we recommend to not use this solver where possible, since it performs relatively poorly (both in solution time and stability of result). Indeed, our example models use the free and open source CBC solver instead, but installing it on Windows requires an extra step. Read the next section for more information on installing alternative solvers.

1.2.3 Updating an existing installation

If following the recommended installation method above, the following command, assuming the conda environment is active, will update Calliope to the newest version

```
$ conda update -c conda-forge calliope
```

1.2.4 Solvers

You need at least one of the solvers supported by Pyomo installed. CBC (open-source) or Gurobi (commercial) are recommended for large problems, and have been confirmed to work with Calliope. Refer to the documentation of your solver on how to install it.

CBC

CBC is our recommended option if you want a free and open-source solver. CBC can be installed via conda on Linux and macOS by running `conda install -c conda-forge coincbc`. Windows binary packages are somewhat more difficult to install, due to limited information on the CBC website, but can be found within their list of binaries. We recommend you download the relevant binary for CBC 2.10 and add *cbc.exe* to a directory known to PATH (e.g. an Anaconda environment 'bin' directory).

GLPK

GLPK is free and open-source, but can take too much time and/or too much memory on larger problems. If using the recommended installation approach above, GLPK is already installed in the `calliope` environment. To install GLPK manually, refer to the GLPK website.

Gurobi

Gurobi is commercial but significantly faster than CBC and GLPK, which is relevant for larger problems. It needs a license to work, which can be obtained for free for academic use by creating an account on gurobi.com.

While Gurobi can be installed via conda (`conda install -c gurobi gurobi`) we recommend downloading and installing the installer from the Gurobi website, as the conda package has repeatedly shown various issues.

After installing, log on to the Gurobi website and obtain a (free academic or paid commercial) license, then activate it on your system via the instructions given online (using the `grbgetkey` command).

CPLEX

Another commercial alternative is CPLEX. IBM offer academic licenses for CPLEX. Refer to the IBM website for details.

1.2.5 Python module requirements

Refer to requirements/base.yml in the Calliope repository for a full and up-to-date listing of required third-party packages.

Some of the key packages Calliope relies on are:

- Pyomo
- Pandas
- Xarray
- Plotly
- Jupyter (optional, but highly recommended, and used for the example notebooks in the tutorials)

1.3 Building a model

In short, a Calliope model works like this: **supply technologies** can take a **resource** from outside of the modeled system and turn it into a specific energy **carrier** in the system. The model specifies one or more **locations** along with the technologies allowed at those locations. **Transmission technologies** can move energy of the same carrier from one location to another, while **conversion technologies** can convert one carrier into another at the same location. **Demand technologies** remove energy from the system, while **storage technologies** can store energy at a specific location. Putting all of these possibilities together allows a modeller to specify as simple or as complex a model as necessary to answer a given research question.

In more technical terms, Calliope allows a modeller to define technologies with arbitrary characteristics by "inheriting" basic traits from a number of included base tech groups – `supply`, `supply_plus`, `demand`, `conversion`, `conversion_plus`, and `transmission`. These groups are described in more detail in *Abstract base technology groups*.

1.3.1 Terminology

The terminology defined here is used throughout the documentation and the model code and configuration files:

- **Technology**: a technology that produces, consumes, converts or transports energy
- **Location**: a site which can contain multiple technologies and which may contain other locations for energy balancing purposes
- **Resource**: a source or sink of energy that can (or must) be used by a technology to introduce into or remove energy from the system
- **Carrier**: an energy carrier that groups technologies together into the same network, for example `electricity` or `heat`.

As more generally in constrained optimisation, the following terms are also used:

- Parameter: a fixed coefficient that enters into model equations
- Variable: a variable coefficient (decision variable) that enters into model equations
- Set: an index in the algebraic formulation of the equations
- Constraint: an equality or inequality expression that constrains one or several variables

1.3.2 Files that define a model

Calliope models are defined through YAML files, which are both human-readable and computer-readable, and CSV files (a simple tabular format) for time series data.

It makes sense to collect all files belonging to a model inside a single model directory. The layout of that directory typically looks roughly like this (+ denotes directories, - files):

```
+ example_model
    + model_config
        - locations.yaml
        - techs.yaml
    + timeseries_data
        - solar_resource.csv
        - electricity_demand.csv
    - model.yaml
    - scenarios.yaml
```

In the above example, the files `model.yaml`, `locations.yaml` and `techs.yaml` together are the model definition. This definition could be in one file, but it is more readable when split into multiple. We use the above layout in the example models and in our research!

Inside the `timeseries_data` directory, timeseries are stored as CSV files. The location of this directory can be specified in the model configuration, e.g. in `model.yaml`.

Note: The easiest way to create a new model is to use the `calliope new` command, which makes a copy of one of the built-in examples models:

```
$ calliope new my_new_model
```

This creates a new directory, `my_new_model`, in the current working directory.

By default, `calliope new` uses the national-scale example model as a template. To use a different template, you can specify the example model to use, e.g.: `--template=urban_scale`.

See also:

YAML configuration file format, *Built-in example models*, *Time series data*

1.3.3 Model configuration (`model`)

The model configuration specifies all aspects of the model to run. It is structured into several top-level headings (keys in the YAML file): `model`, `techs`, `locations`, `links`, and `run`. We will discuss each of these in turn, starting with `model`:

```
model:
    name: 'My energy model'
    timeseries_data_path: 'timeseries_data'
    reserve_margin:
        power: 0
    subset_time: ['2005-01-01', '2005-01-05']
```

Besides the model's name (`name`) and the path for CSV time series data (`timeseries_data_path`), group constraints can be set, like `reserve_margin`.

To speed up model runs, the above example specifies a time subset to run the model over only five days of time series data (`subset_time: ['2005-01-01', '2005-01-05']`)– this is entirely optional. Usually, a full model will contain at least one year of data, but subsetting time can be useful to speed up a model for testing purposes.

See also:

National scale example model, *Model configuration*

1.3.4 Technologies (techs)

The `techs` section in the model configuration specifies all of the model's technologies. In our current example, this is in a separate file, `model_config/techs.yaml`, which is imported into the main `model.yaml` file alongside the file for locations described further below:

```
import:
    - 'model_config/techs.yaml'
    - 'model_config/locations.yaml'
```

Note: The `import` statement can specify a list of paths to additional files to import (the imported files, in turn, may include further files, so arbitrary degrees of nested configurations are possible). The `import` statement can either give an absolute path or a path relative to the importing file.

The following example shows the definition of a `ccgt` technology, i.e. a combined cycle gas turbine that delivers electricity:

```
ccgt:
    essentials:
        name: 'Combined cycle gas turbine'
        color: '#FDC97D'
        parent: supply
        carrier_out: power
    constraints:
        resource: inf
        energy_eff: 0.5
        energy_cap_max: 40000  # kW
        energy_cap_max_systemwide: 100000  # kW
        energy_ramping: 0.8
        lifetime: 25
    costs:
        monetary:
            interest_rate: 0.10
            energy_cap: 750  # USD per kW
            om_con: 0.02  # USD per kWh
```

Each technology must specify some `essentials`, most importantly a name, the abstract base technology it is inheriting from (`parent`), and its energy carrier (`carrier_out` in the case of a `supply` technology). Specifying a `color` is optional but useful for using the built-in visualisation tools (see *Analysing a model*).

The `constraints` section gives all constraints for the technology, such as allowed capacities, conversion efficiencies, the life time (used in levelised cost calculations), and the resource it consumes (in the above example, the resource is set to infinite via `inf`).

The `costs` section gives costs for the technology. Calliope uses the concept of "cost classes" to allow accounting for more than just monetary costs. The above example specifies only the `monetary` cost class, but any number of other

classes could be used, for example `co2` to account for emissions. Additional cost classes can be created simply by adding them to the definition of costs for a technology.

By default, only the `monetary` cost class is used in the objective function, i.e., the default objective is to minimize total costs.

Multiple cost classes can be considered in the objective by setting the *cost_class* key. It must be a dictionary of cost classes and their weights in the objective, e.g. `objective_options: {'cost_class': {'monetary': 1, 'emissions': 0.1}}`. In this example, monetary costs are summed as usual and emissions are added to this, scaled by 0.1 (emulating a carbon price).

To use a different sense (minimize/maximize) you can set *sense*: `objective_options: {'cost_class': ..., 'sense': 'minimize'}`.

To use a single alternative cost class, disabling the consideration of the default *monetary*, set the weight of the monetary cost class to zero to stop considering it and the weight of another cost class to a non-zero value, e.g. `objective_options: {'cost_class': {'monetary': 0, 'emissions': 1}}`.

See also:

Per-tech constraints, *Per-tech costs*, *tutorials*, *built-in examples*

Allowing for unmet demand

For a model to find a feasible solution, supply must always be able to meet demand. To avoid the solver failing to find a solution, you can ensure feasibility:

```
run:
    ensure_feasibility: true
```

This will create an `unmet_demand` decision variable in the optimisation, which can pick up any mismatch between supply and demand, across all energy carriers. It has a very high cost associated with its use, so it will only appear when absolutely necessary.

Note: When ensuring feasibility, you can also set a big M value (`run.bigM`). This is the "cost" of unmet demand. It is possible to make model convergence very slow if bigM is set too high. default bigM is $1x10^{9}$, but should be close to the maximum total system cost that you can imagine. This is perhaps closer to $1x10^{6}$ for urban scale models.

1.3.5 Time series data

For parameters that vary in time, time series data can be added to a model in two ways:

- by reading in CSV files
- by passing `pandas` dataframes as arguments in `calliope.Model` called from a python session.

Reading in CSV files is possible from both the command-line tool as well running interactively with python (see *Running a model* for details). However, passing dataframes as arguments in `calliope.Model` is possible only when running from a python session.

Reading in CSV files

To read in CSV files, specify `resource: file=filename.csv` to pick the desired CSV file from within the configured timeseries data path (`model.timeseries_data_path`).

By default, Calliope looks for a column in the CSV file with the same name as the location. It is also possible to specify a column to use when setting `resource` per location, by giving the column name with a colon following the filename: `resource: file=filename.csv:column`

For example, a simple photovoltaic (PV) tech using a time series of hour-by-hour electricity generation data might look like this:

```
pv:
    essentials:
        name: 'Rooftop PV'
        color: '#B59C2B'
        parent: supply
        carrier_out: power
    constraints:
        resource: file=pv_resource.csv
        energy_cap_max: 10000  # kW
```

By default, Calliope expects time series data in a model to be indexed by ISO 8601 compatible time stamps in the format `YYYY-MM-DD hh:mm:ss`, e.g. `2005-01-01 00:00:00`. This can be changed by setting `model.timeseries_dateformat` based on `strftime` directives <http://strftime.org/>`_, which defaults to ``'%Y-%m-%d %H:%M:%S'`.

For example, the first few lines of a CSV file, called `pv_resource.csv` giving a resource potential for two locations might look like this, with the first column in the file always being read as the date-time index:

```
,location1,location2
2005-01-01 00:00:00,0,0
2005-01-01 01:00:00,0,11
2005-01-01 02:00:00,0,18
2005-01-01 03:00:00,0,49
2005-01-01 04:00:00,11,110
2005-01-01 05:00:00,45,300
2005-01-01 06:00:00,90,458
```

Reading in timeseries from `pandas` dataframes

When running models from python scripts or shells, it is also possible to pass timeseries directly as `pandas` dataframes. This is done by specifying `resource: df=tskey` where `tskey` is the key in a dictionary containing the relevant dataframes. For example, if the same timeseries as above is to be passed, a dataframe called `pv_resource` may be in the python namespace:

```
pv_resource

t                     location1  location2
2005-01-01 00:00:00           0          0
2005-01-01 01:00:00           0         11
2005-01-01 02:00:00           0         18
2005-01-01 03:00:00           0         49
2005-01-01 04:00:00          11        110
```

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```
2005-01-01 05:00:00          45         300
2005-01-01 06:00:00          90         458
```

To pass this timeseries into the model, create a dictionary, called `timeseries_dataframes` here, containing all relevant timeseries identified by their `tskey`. In this case, this has only one key, called `pv_resource`:

```
timeseries_dataframes = {'pv_resource': pv_resource}
```

The keys in this dictionary must match the `tskey` specified in the YAML files. In this example, specifying `resource: df=pv_resource` will identify the `pv_resource` key in `timeseries_dataframes`. All relevant timeseries must be put in this dictionary. For example, if a model contains three timeseries referred to in the configuration YAML files, called `demand_1`, `demand_2` and `pv_resource`, the `timeseries_dataframes` dictionary may look like

```
timeseries_dataframes = {'demand_1': demand_1,
                         'demand_2': demand_2,
                         'pv_resource': pv_resource}
```

where `demand_1`, `demand_2` and `pv_resource` are dataframes of the relevant timeseries. The `timeseries_dataframes` can then be called in `calliope.Model`:

```
model = calliope.Model('model.yaml', timeseries_dataframes=timeseries_dataframes)
```

Just like when using CSV files (see above), Calliope looks for a column in the dataframe with the same name as the location. It is also possible to specify a column to use when setting `resource` per location, by giving the column name with a colon following the filename: `resource: df=tskey:column`.

The time series index must be ISO 8601 compatible time stamps and can be a standard `pandas` DateTimeIndex (see discussion above).

Note:

- If a parameter is not explicit in time and space, it can be specified as a single value in the model definition (or, using location-specific definitions, be made spatially explicit). This applies both to parameters that never vary through time (for example, cost of installed capacity) and for those that may be time-varying (for example, a technology's available resource). However, each model must contain at least one time series.
- Only the subset of parameters listed in *file_allowed* in the *model configuration* can be loaded from file or dataframe in this way. It is advised not to update this default list unless you are developing the core code, since the model will likely behave unexpectedly.
- You _cannot_ have a space around the = symbol when pointing to a timeseries file or dataframe key, i.e. `resource: file = filename.csv` is not valid.
- If running from a command line interface (see *Running a model*), timeseries must be read from CSV and cannot be passed from dataframes via `df=...`.
- It's possible to mix reading in from CSVs and dataframes, by setting some config values as `file=...` and some as `df=...`.
- The default value of `timeseries_dataframes` is `None`, so if you want to read all timeseries in from CSVs, you can omit this argument. When running from command line, this is done automatically.

1.3.6 Locations and links (`locations`, `links`)

A model can specify any number of locations. These locations are linked together by transmission technologies. By consuming an energy carrier in one location and outputting it in another, linked location, transmission technologies allow resources to be drawn from the system at a different location from where they are brought into it.

The `locations` section specifies each location:

```
locations:
    region1:
        coordinates: {lat: 40, lon: -2}
        techs:
            unmet_demand_power:
            demand_power:
            ccgt:
                constraints:
                    energy_cap_max: 30000
```

Locations can optionally specify `coordinates` (used in visualisation or to compute distance between them) and must specify `techs` allowed at that location. As seen in the example above, each allowed tech must be listed, and can optionally specify additional location-specific parameters (constraints or costs). If given, location-specific parameters supersede any group constraints a technology defines in the `techs` section for that location.

The `links` section specifies possible transmission links between locations in the form `location1,location2`:

```
links:
    region1,region2:
        techs:
            ac_transmission:
                constraints:
                    energy_cap_max: 10000
                costs.monetary:
                    energy_cap: 100
```

In the above example, an high-voltage AC transmission line is specified to connect `region1` with `region2`. For this to work, a `transmission` technology called `ac_transmission` must have previously been defined in the model's `techs` section. There, it can be given group constraints or costs. As in the case of locations, the `links` section can specify per-link parameters (constraints or costs) that supersede any model-wide parameters.

The modeller can also specify a distance for each link, and use per-distance constraints and costs for transmission technologies.

See also:

Per-tech constraints, *Per-tech costs*.

1.3.7 Run configuration (`run`)

The only required setting in the run configuration is the solver to use:

```
run:
    solver: cbc
    mode: plan
```

the most important parts of the `run` section are `solver` and `mode`. A model can run in planning mode (`plan`), operational mode (`operate`), or SPORES mode (`spores`). In planning mode, capacities are determined by the model,

whereas in operational mode, capacities are fixed and the system is operated with a receding horizon control algorithm. In SPORES mode, the model is first run in planning mode, then run *N* number of times to find alternative system configurations with similar monetary cost, but maximally different choice of technology capacity and location.

Possible options for solver include `glpk`, `gurobi`, `cplex`, and `cbc`. The interface to these solvers is done through the Pyomo library. Any solver compatible with Pyomo should work with Calliope.

For solvers with which Pyomo provides more than one way to interface, the additional `solver_io` option can be used. In the case of Gurobi, for example, it is usually fastest to use the direct Python interface:

```
run:
    solver: gurobi
    solver_io: python
```

Note: The opposite is currently true for CPLEX, which runs faster with the default `solver_io`.

Further optional settings, including debug settings, can be specified in the run configuration.

See also:

Run configuration, *Troubleshooting*, *Specifying custom solver options*, *documentation on operational mode*, *documentation on SPORES mode*.

1.3.8 Scenarios and overrides

To make it easier to run a given model multiple times with slightly changed settings or constraints, for example, varying the cost of a key technology, it is possible to define and apply scenarios and overrides. "Overrides" are blocks of YAML that specify configurations that expand or override parts of the base model. "Scenarios" are combinations of any number of such overrides. Both are specified at the top level of the model configuration, as in this example `model.yaml` file:

```
scenarios:
    high_cost_2005: ["high_cost", "year2005"]
    high_cost_2006: ["high_cost", "year2006"]

overrides:
    high_cost:
        techs.onshore_wind.costs.monetary.energy_cap: 2000
    year2005:
        model.subset_time: ['2005-01-01', '2005-12-31']
    year2006:
        model.subset_time: ['2006-01-01', '2006-12-31']

model:
    ...

run:
    ...
```

Each override is given by a name (e.g. `high_cost`) and any number of model settings – anything in the model configuration can be overridden by an override. In the above example, one override defines higher costs for an `onshore_wind` tech while the two other overrides specify different time subsets, so would run an otherwise identical model over two different periods of time series data.

One or several overrides can be applied when running a model, as described in *Running a model*. Overrides can also be combined into scenarios to make applying them at run-time easier. Scenarios consist of a name and a list of override names which together form that scenario.

Scenarios and overrides can be used to generate scripts that run a single Calliope model many times, either sequentially, or in parallel on a high-performance cluster (see *Generating scripts to run a model many times*).

Note: Overrides can also import other files. This can be useful if many overrides are defined which share large parts of model configuration, such as different levels of interconnection between model zones. See *Importing other YAML files in overrides* for details.

See also:

Generating scripts to run a model many times, *Importing other YAML files in overrides*

1.4 Running a model

There are essentially three ways to run a Calliope model:

1. With the `calliope run` command-line tool.
2. By programmatically creating and running a model from within other Python code, or in an interactive Python session.
3. By generating and then executing scripts with the `calliope generate_runs` command-line tool, which is primarily designed for running many scenarios on a high-performance cluster.

1.4.1 Running with the command-line tool

We can easily run a model after creating it (see *Building a model*), saving results to a single NetCDF file for further processing

```
$ calliope run testmodel/model.yaml --save_netcdf=results.nc
```

The `calliope run` command takes the following options:

- `--save_netcdf={filename.nc}`: Save complete model, including results, to the given NetCDF file. This is the recommended way to save model input and output data into a single file, as it preserves all data fully, and allows later reconstruction of the Calliope model for further analysis.
- `--save_csv={directory name}`: Save results as a set of CSV files to the given directory. This can be handy if the modeler needs results in a simple text-based format for further processing with a tool like Microsoft Excel.
- `--save_plots={filename.html}`: Save interactive plots to the given HTML file (see *Analysing a model* for further details on the plotting functionality).
- `--debug`: Run in debug mode, which prints more internal information, and is useful when troubleshooting failing models.
- `--scenario={scenario}` and `--override_dict={yaml_string}`: Specify a scenario, or one or several overrides, to apply to the model, or apply specific overrides from a YAML string (see below for more information)
- `--help`: Show all available options.

Multiple options can be specified, for example, saving NetCDF, CSV, and HTML plots simultaneously

```
$ calliope run testmodel/model.yaml --save_netcdf=results.nc --save_
↪csv=outputs --save_plots=plots.html
```

Warning: Unlike in versions prior to 0.6.0, the command-line tool in Calliope 0.6.0 and upward does not save results by default – the modeller must specify one of the `-save` options.

Applying a scenario or override

The `--scenario` can be used in three different ways:

- It can be given the name of a scenario defined in the model configuration, as in `--scenario=my_scenario`
- It can be given the name of a single override defined in the model configuration, as in `--scenario=my_override`
- It can be given a comma-separated string of several overrides defined in the model configuration, as in `--scenario=my_override_1,my_override_2`

In the latter two cases, the given override(s) is used to implicitly create a "scenario" on-the-fly when running the model. This allows quick experimentation with different overrides without explicitly defining a scenario combining them.

Assuming we have specified an override called `milp` in our model configuration, we can apply it to our model with

```
$ calliope run testmodel/model.yaml --scenario=milp --save_netcdf=results.nc
```

Note that if both a scenario and an override with the same name, such as `milp` in the above example, exist, Calliope will raise an error, as it will not be clear which one the user wishes to apply.

It is also possible to use the *–override_dict* option to pass a YAML string that will be applied after anything applied through `--scenario`

```
$ calliope run testmodel/model.yaml --override_dict="{'model.subset_time': [
↪'2005-01-01', '2005-01-31']}" --save_netcdf=results.nc
```

See also:

Analysing a model, *Scenarios and overrides*

1.4.2 Running interactively with Python

The most basic way to run a model programmatically from within a Python interpreter is to create a *Model* instance with a given `model.yaml` configuration file, and then call its *run()* method:

```
import calliope
model = calliope.Model('path/to/model.yaml')
model.run()
```

Note: If `config` is not specified (i.e. `model = Model()`), an error is raised. See *Built-in example models* for information on instantiating a simple example model without specifying a custom model configuration.

Other ways to load a model interactively are:

- Passing an `AttrDict` or standard Python dictionary to the *Model* constructor, with the same nested format as the YAML model configuration (top-level keys: `model`, `run`, `locations`, `techs`).
- Loading a previously saved model from a NetCDF file with `model = calliope.read_netcdf('path/to/saved_model.nc')`. This can either be a pre-processed model saved before its `run` method was called, which will include input data only, or a completely solved model, which will include input and result data.

After instantiating the `Model` object, and before calling the `run()` method, it is possible to manually inspect and adjust the configuration of the model. The pre-processed inputs are all held in the xarray Dataset `model.inputs`.

After the model has been solved, an xarray Dataset containing results (`model.results`) can be accessed. At this point, the model can be saved with either *to_csv()* or *to_netcdf()*, which saves all inputs and results, and is equivalent to the corresponding `--save` options of the command-line tool.

See also:

An example of interactive running in a Python session, which also demonstrates some of the analysis possibilities after running a model, is given in the *tutorials*. You can download and run the embedded notebooks on your own machine (if both Calliope and the Jupyter Notebook are installed).

Scenarios and overrides

There are two ways to override a base model when running interactively, analogously to the use of the command-line tool (see *Applying a scenario or override* above):

1. By setting the *scenario* argument, e.g.:

```
model = calliope.Model('model.yaml', scenario='milp')
```

2. By passing the *override_dict* argument, which is a Python dictionary, an `AttrDict`, or a YAML string of overrides:

```
model = calliope.Model(
    'model.yaml',
    override_dict={'run.solver': 'gurobi'}
)
```

Note: Both *scenario* and *override_dict* can be defined at once. They will be applied in order, such that scenarios are applied first, followed by dictionary overrides. As such, the *override_dict* can be used to override scenarios.

Tracking progress

When running Calliope in the command line, logging of model pre-processing and solving occurs automatically. Interactively, for example in a Jupyter notebook, you can enable verbose logging by setting the log level using `calliope.set_log_verbosity(level)` immediately after importing the Calliope package. By default, `calliope.set_log_verbosity()` also sets the log level for the backend model to *DEBUG*, which turns on output of solver output. This can be disabled by `calliope.set_log_verbosity(level, include_solver_output=False)`. Possible log levels are (from least to most verbose):

1. *CRITICAL*: only show critical errors.
2. *ERROR*: only show errors.
3. *WARNING*: show errors and warnings (default level).

4. *INFO*: show errors, warnings, and informative messages. Calliope uses the INFO level to show a message at each stage of pre-processing, sending the model to the solver, and post-processing, including timestamps.
5. *DEBUG*: SOLVER logging, with heavily verbose logging of a number of function outputs. Only for use when troubleshooting failing runs or developing new functionality in Calliope.

1.4.3 Generating scripts for many model runs

Scripts to simplify the creation and execution of a large number of Calliope model runs are generated with the `calliope generate_runs` command-line tool. More detail on this is available in *Generating scripts to run a model many times*.

1.4.4 Improving solution times

Large models will take time to solve. The easiest is often to just let a model run on a remote device (another computer, or a high performance computing cluster) and forget about it until it is done. However, if you need results *now*, there are ways to improve solution time.

Details on strategies to improve solution times are given in *Troubleshooting*.

1.4.5 Debugging failing runs

What will typically go wrong, in order of decreasing likelihood:

- The model is improperly defined or missing data. Calliope will attempt to diagnose some common errors and raise an appropriate error message.
- The model is consistent and properly defined but infeasible. Calliope will be able to construct the model and pass it on to the solver, but the solver (after a potentially long time) will abort with a message stating that the model is infeasible.
- There is a bug in Calliope causing the model to crash either before being passed to the solver, or after the solver has completed and when results are passed back to Calliope.

Calliope provides help in diagnosing all of these model issues. For details, see *Troubleshooting*.

1.5 Analysing a model

Calliope inputs and results are designed for easy handling. Whatever software you prefer to use for data processing, either the NetCDF or CSV output options should provide a path to importing your Calliope results. If you prefer to not worry about writing your own scripts, then we have that covered too! The built-in plotting functions in `plot` are built on Plotly's interactive visualisation tools to bring your data to life.

1.5.1 Accessing model data and results

A model which solved successfully has two primary Datasets with data of interest:

- `model.inputs`: contains all input data, such as renewable resource capacity factors
- `model.results`: contains all results data, such as dispatch decisions and installed capacities

In both of these, variables are indexed over concatenated sets of locations and technologies, over a dimension we call `loc_techs`. For example, if a technology called `boiler` only exists in location `X1` and not in locations `X2` or `X3`, then it will have a single entry in the loc_techs dimension called `X1::boiler`. For parameters which also consider

different energy carriers, we use a `loc_tech_carrier` dimension, such that we would have, in the case of the prior boiler example, `X1::boiler::heat`.

This concatenated set formulation is memory-efficient but cumbersome to deal with, so the `model.get_formatted_array(name_of_variable)` function can be used to retrieve a DataArray indexed over separate dimensions (any of *techs*, *locs*, *carriers*, *costs*, *timesteps*, depending on the desired variable).

Note: On saving to CSV (see the *command-line interface documentation*), all variables are saved to a single file each, which are always indexed over all dimensions rather than just the concatenated dimensions.

1.5.2 Visualising results

In an interactive Python session, there are four primary visualisation functions: `capacity`, `timeseries`, `transmission`, and `summary`. To gain access to result visualisation without the need to interact with Python, the `summary` plot can also be accessed from the command line interface (*see below*).

Refer to the *API documentation for the analysis module* for an overview of available analysis functionality.

Refer to the *tutorials* for some basic analysis techniques.

Plotting time series

The following example shows a timeseries plot of the built-in urban scale example model:

In Python, we get this function by calling `model.plot.timeseries()`. It includes all relevant timeseries information, from both inputs and results. We can force it to only have particular results in the dropdown menu:

```
# Only inputs or only results
model.plot.timeseries(array='inputs')
model.plot.timeseries(array='results')

# Only consumed resource
model.plot.timeseries(array='resource_con')

# Only consumed resource and 'power' carrier flow
model.plot.timeseries(array=['power', 'resource_con'])
```

The data used to build the plots can also be subset and ordered by using the `subset` argument. This uses xarray's 'loc' indexing functionality to access subsets of data:

```
# Only show region1 data (rather than the default, which is a sum of all locations)
model.plot.timeseries(subset={'locs': ['region1']})

# Only show a subset of technologies
model.plot.timeseries(subset={'techs': ['ccgt', 'csp']})

# Assuming our model has three techs, 'ccgt', 'csp', and 'battery',
# specifying `subset` lets us order them in the stacked barchart
model.plot.timeseries(subset={'techs': ['ccgt', 'battery', 'csp']})
```

When aggregating model timesteps with clustering methods, the timeseries plots are adjusted accordingly (example from the built-in `time_clustering` example model):

See also:

API documentation for the analysis module

Plotting capacities

The following example shows a capacity plot of the built-in urban scale example model:

Functionality is similar to timeseries, this time called by `model.plot.capacity()`. Here we show capacity limits set at input and chosen capacities at output. Choosing dropdowns and subsetting works in the same way as for timeseries plots

Plotting transmission

The following example shows a transmission plot of the built-in urban scale example model:

By calling `model.plot.transmission()` you will see installed links, their capacities (on hover), and the locations of the nodes. This functionality only works if you have physically pinpointed your locations using the `coordinates` key for your location.

The above plot uses Mapbox to overlay our transmission plot on Openstreetmap. By creating an account at Mapbox and acquiring a Mapbox access token, you can also create similar visualisations by giving the token to the plotting function: `model.plot.transmission(mapbox_access_token='your token here')`.

Without the token, the plot will fall back on simple country-level outlines. In this urban scale example, the background is thus just grey (zoom out to see the UK!):

Note: If the coordinates were in *x* and *y*, not *lat* and *lon*, the transmission trace would be given on a cartesian plot.

Plotting flows

The following example shows an energy flow plot of the built-in urban scale example model:

By calling `model.plot.flows()` you will see a plot similar to *transmission*. However, you can see carrier production at each node and along links, at every timestep (controlled by moving a slider). This functionality only works if you have physically pinpointed your locations using the `coordinates` key for your location. It is possible to look at only a subset of the timesteps in the model using the *timestep_index_subset* argument, or to show only every `X` timestep (where `X` is an integer) using the *timestep_cycle* argument.

Note: If the timestep dimension is particularly large in your model, you will find this visualisation to be slow. Time subsetting is recommended for such a case.

If you cannot see the carrier production for a technology on hovering, it is likely masked by another technology at the same location or on the same link. Hide the masking technology to get the hover info for the technology below.

Summary plots

If you want all the data in one place, you can run `model.plot.summary(to_file='path/to/file.html')`, which will build a HTML file of all the interactive plots (maintaining the interactivity) and save it to 'path/to/file.html'. This HTML file can be opened in a web browser to show all the plots. This funcionality is made available in the command line interface by using the command `--save_plots=filename.html` when running the model.

See an example of such a HTML plot here.

See also:

Running with the command-line tool

Saving publication-quality SVG figures

On calling any of the three primary plotting functions, you can also set `to_file=path/to/file.svg` for a high quality vector graphic to be saved. This file can be prepared for publication in programs like Inkscape.

Note: For similar results in the command line interface, you'll currently need to save your model to netcdf (`--save_netcdf={filename.nc}`) then load it into a Calliope Model object in Python. Once there, you can use the above functions to get your SVGs.

1.5.3 Reading solutions

Calliope provides functionality to read a previously-saved model from a single NetCDF file:

```
solved_model = calliope.read_netcdf('my_saved_model.nc')
```

In the above example, the model's input data will be available under `solved_model.inputs`, while the results (if the model had previously been solved) are available under `solved_model.results`.

Both of these are xarray.Datasets and can be further processed with Python.

See also:

The xarray documentation should be consulted for further information on dealing with Datasets. Calliope's NetCDF files follow the CF conventions and can easily be processed with any other tool that can deal with NetCDF.

1.6 Tutorials

The tutorials are based on the built-in example models, they explain the key steps necessary to set up and run simple models. Refer to the other parts of the documentation for more detailed information on configuring and running more complex models. The built-in examples are simple on purpose, to show the key components of a Calliope model with which models of arbitrary complexity can be built.

The *first tutorial* builds a model for part of a national grid, exhibiting the following Calliope functionality:

- Use of supply, supply_plus, demand, storage and transmission technologies
- Nested locations
- Multiple cost types

The *second tutorial* builds a model for part of a district network, exhibiting the following Calliope functionality:

- Use of supply, demand, conversion, conversion_plus, and transmission technologies
- Use of multiple energy carriers
- Revenue generation, by carrier export

The *third tutorial* extends the second tutorial, exhibiting binary and integer decision variable functionality (extended an LP model to a MILP model)

1.6.1 Tutorial 1: national scale

This example consists of two possible power supply technologies, a power demand at two locations, the possibility for battery storage at one of the locations, and a transmission technology linking the two. The diagram below gives an overview:

Fig. 1: Overview of the built-in national-scale example model

Supply-side technologies

The example model defines two power supply technologies.

The first is `ccgt` (combined-cycle gas turbine), which serves as an example of a simple technology with an infinite resource. Its only constraints are the cost of built capacity (`energy_cap`) and a constraint on its maximum built capacity.

Fig. 2: The layout of a supply node, in this case `ccgt`, which has an infinite resource, a carrier conversion efficiency ($energy_{eff}$), and a constraint on its maximum built $energy_{cap}$ (which puts an upper limit on $energy_{prod}$).

The definition of this technology in the example model's configuration looks as follows:

```
ccgt:
    essentials:
        name: 'Combined cycle gas turbine'
        color: '#E37A72'
        parent: supply
        carrier_out: power
    constraints:
        resource: inf
        energy_eff: 0.5
        energy_cap_max: 40000  # kW
        energy_cap_max_systemwide: 100000  # kW
        energy_ramping: 0.8
        lifetime: 25
    costs:
        monetary:
            interest_rate: 0.10
            energy_cap: 750  # USD per kW
            om_con: 0.02  # USD per kWh
```

There are a few things to note. First, `ccgt` defines essential information: a name, a color (given as an HTML color code, for later visualisation), its parent, `supply`, and its carrier_out, `power`. It has set itself up as a power supply technology.

This is followed by the definition of constraints and costs (the only cost class used is monetary, but this is where other "costs", such as emissions, could be defined).

Note: There are technically no restrictions on the units used in model definitions. Usually, the units will be kW and kWh, alongside a currency like USD for costs. It is the responsibility of the modeler to ensure that units are correct and consistent. Some of the analysis functionality in the `postprocess` module assumes that kW and kWh are used when drawing figure and axis labels, but apart from that, there is nothing preventing the use of other units.

The second technology is `csp` (concentrating solar power), and serves as an example of a complex supply_plus technology making use of:

- a finite resource based on time series data
- built-in storage
- plant-internal losses (`parasitic_eff`)

Fig. 3: The layout of a more complex node, in this case `csp`, which makes use of most node-level functionality available.

This definition in the example model's configuration is more verbose:

```
csp:
    essentials:
        name: 'Concentrating solar power'
        color: '#F9CF22'
        parent: supply_plus
        carrier_out: power
    constraints:
        storage_cap_max: 614033
        energy_cap_per_storage_cap_max: 1
        storage_loss: 0.002
        resource: file=csp_resource.csv
        resource_unit: energy_per_area
        energy_eff: 0.4
        parasitic_eff: 0.9
        resource_area_max: inf
        energy_cap_max: 10000
        lifetime: 25
    costs:
        monetary:
            interest_rate: 0.10
            storage_cap: 50
            resource_area: 200
            resource_cap: 200
            energy_cap: 1000
            om_prod: 0.002
```

Again, `csp` has the definitions for name, color, parent, and carrier_out. Its constraints are more numerous: it defines a maximum storage capacity (`storage_cap_max`), an hourly storage loss rate (`storage_loss`), then specifies that its resource should be read from a file (more on that below). It also defines a carrier conversion efficiency of 0.4 and a parasitic efficiency of 0.9 (i.e., an internal loss of 0.1). Finally, the resource collector area and the installed carrier conversion capacity are constrained to a maximum.

The costs are more numerous as well, and include monetary costs for all relevant components along the conversion from

resource to carrier (power): storage capacity, resource collector area, resource conversion capacity, energy conversion capacity, and variable operational and maintenance costs. Finally, it also overrides the default value for the monetary interest rate.

Storage technologies

The second location allows a limited amount of battery storage to be deployed to better balance the system. This technology is defined as follows:

Fig. 4: A storage node with an $energy_{eff}$ and $storage_{loss}$.

```
battery:
    essentials:
        name: 'Battery storage'
        color: '#3B61E3'
        parent: storage
        carrier: power
    constraints:
        energy_cap_max: 1000  # kW
        storage_cap_max: inf
        energy_cap_per_storage_cap_max: 4
        energy_eff: 0.95  # 0.95 * 0.95 = 0.9025 round trip efficiency
        storage_loss: 0  # No loss over time assumed
        lifetime: 25
    costs:
        monetary:
            interest_rate: 0.10
            storage_cap: 200  # USD per kWh storage capacity
```

The contraints give a maximum installed generation capacity for battery storage together with a maximum ratio of energy capacity to storage capacity (`energy_cap_per_storage_cap_max`) of 4, which in turn limits the storage capacity. The ratio is the charge/discharge rate / storage capacity (a.k.a the battery *reservoir*). In the case of a storage technology, `energy_eff` applies twice: on charging and discharging. In addition, storage technologies can lose stored energy over time – in this case, we set this loss to zero.

Other technologies

Three more technologies are needed for a simple model. First, a definition of power demand:

Fig. 5: A simple demand node.

```
demand_power:
    essentials:
        name: 'Power demand'
        color: '#072486'
        parent: demand
        carrier: power
```

Power demand is a technology like any other. We will associate an actual demand time series with the demand technology later.

What remains to set up is a simple transmission technology. Transmission technologies (like conversion technologies) look different than other nodes, as they link the carrier at one location to the carrier at another (or, in the case of conversion, one carrier to another at the same location):

Fig. 6: A simple transmission node with an $energy_{eff}$.

```yaml
ac_transmission:
    essentials:
        name: 'AC power transmission'
        color: '#8465A9'
        parent: transmission
        carrier: power
    constraints:
        energy_eff: 0.85
        lifetime: 25
    costs:
        monetary:
            interest_rate: 0.10
            energy_cap: 200
            om_prod: 0.002

free_transmission:
    essentials:
        name: 'Local power transmission'
        color: '#6783E3'
        parent: transmission
        carrier: power
    constraints:
        energy_cap_max: inf
        energy_eff: 1.0
    costs:
        monetary:
            om_prod: 0
```

`ac_transmission` has an efficiency of 0.85, so a loss during transmission of 0.15, as well as some cost definitions.

`free_transmission` allows local power transmission from any of the csp facilities to the nearest location. As the name suggests, it applies no cost or efficiency losses to this transmission.

Locations

In order to translate the model requirements shown in this section's introduction into a model definition, five locations are used: `region-1`, `region-2`, `region1-1`, `region1-2`, and `region1-3`.

The technologies are set up in these locations as follows:

Fig. 7: Locations and their technologies in the example model

Let's now look at the first location definition:

```
region1:
    coordinates: {lat: 40, lon: -2}
    techs:
        demand_power:
            constraints:
                resource: file=demand-1.csv:demand
        ccgt:
            constraints:
                energy_cap_max: 30000 # increased to ensure no unmet_demand in first␣
↪timestep
```

There are several things to note here:

- The location specifies a dictionary of technologies that it allows (`techs`), with each key of the dictionary referring to the name of technologies defined in our `techs.yaml` file. Note that technologies listed here must have been defined elsewhere in the model configuration.
- It also overrides some options for both `demand_power` and `ccgt`. For the latter, it simply sets a location-specific maximum capacity constraint. For `demand_power`, the options set here are related to reading the demand time series from a CSV file. CSV is a simple text-based format that stores tables by comma-separated rows. Note that we did not define any `resource` option in the definition of the `demand_power` technology. Instead, this is done directly via a location-specific override. For this location, the file `demand-1.csv` is loaded and the column `demand` is taken (the text after the colon). If no column is specified, Calliope will assume that the column name matches the location name `region1-1`. Note that in Calliope, a supply is positive and a demand is negative, so the stored CSV data will be negative.
- Coordinates are defined by latitude (`lat`) and longitude (`lon`), which will be used to calculate distance of transmission lines (unless we specify otherwise later on) and for location-based visualisation.

The remaining location definitions look like this:

```
region2:
    coordinates: {lat: 40, lon: -8}
    techs:
        demand_power:
            constraints:
                resource: file=demand-2.csv:demand
        battery:

region1-1.coordinates: {lat: 41, lon: -2}
region1-2.coordinates: {lat: 39, lon: -1}
region1-3.coordinates: {lat: 39, lon: -2}

region1-1, region1-2, region1-3:
    techs:
        csp:
```

`region2` is very similar to `region1`, except that it does not allow the `ccgt` technology. The three `region1-` locations are defined together, except for their location coordinates, i.e. they each get the exact same configuration. They allow only the `csp` technology, this allows us to model three possible sites for CSP plants.

For transmission technologies, the model also needs to know which locations can be linked, and this is set up in the model configuration as follows:

```
region1,region2:
    techs:
```

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```
        ac_transmission:
            constraints:
                energy_cap_max: 10000
region1,region1-1:
    techs:
        free_transmission:
region1,region1-2:
    techs:
        free_transmission:
region1,region1-3:
    techs:
        free_transmission:
```

We are able to override constraints for transmission technologies at this point, such as the maximum capacity of the specific `region1` to `region2` link shown here.

Running the model

We now take you through running the model in a Jupyter notebook, which you can view here. After clicking on that link, you can also download and run the notebook yourself (you will need to have Calliope installed).

1.6.2 Tutorial 2: urban scale

This example consists of two possible sources of electricity, one possible source of heat, and one possible source of simultaneous heat and electricity. There are three locations, each describing a building, with transmission links between them. The diagram below gives an overview:

Fig. 8: Overview of the built-in urban-scale example model

Supply technologies

This example model defines three supply technologies.

The first two are `supply_gas` and `supply_grid_power`, referring to the supply of `gas` (natural gas) and `electricity`, respectively, from the national distribution system. These 'inifinitely' available national commodities can become energy carriers in the system, with the cost of their purchase being considered at supply, not conversion.

Fig. 9: The layout of a simple supply technology, in this case `supply_gas`, which has a resource input and a carrier output. A carrier conversion efficiency ($energy_{eff}$) can also be applied (although isn't considered for our supply technologies in this problem).

The definition of these technologies in the example model's configuration looks as follows:

```
supply_grid_power:
    essentials:
        name: 'National grid import'
        color: '#C5ABE3'
        parent: supply
```

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```
        carrier: electricity
    constraints:
        resource: inf
        energy_cap_max: 2000
        lifetime: 25
    costs:
        monetary:
            interest_rate: 0.10
            energy_cap: 15
            om_con: 0.1 # 10p/kWh electricity price #ppt

supply_gas:
    essentials:
        name: 'Natural gas import'
        color: '#C98AAD'
        parent: supply
        carrier: gas
    constraints:
        resource: inf
        energy_cap_max: 2000
        lifetime: 25
    costs:
        monetary:
            interest_rate: 0.10
            energy_cap: 1
            om_con: 0.025 # 2.5p/kWh gas price #ppt
```

The final supply technology is `pv` (solar photovoltaic power), which serves as an inflexible supply technology. It has a time-dependant resource availablity, loaded from file, a maximum area over which it can capture its resource (`resource_area_max`) and a requirement that all available resource must be used (`force_resource: True`). This emulates the reality of solar technologies: once installed, their production matches the availability of solar energy.

The efficiency of the DC to AC inverter (which occurs after conversion from resource to energy carrier) is considered in `parasitic_eff` and the `resource_area_per_energy_cap` gives a link between the installed area of solar panels to the installed capacity of those panels (i.e. kWp).

In most cases, domestic PV panels are able to export excess energy to the national grid. We allow this here by specifying an `export_carrier`. Revenue for export will be considered on a per-location basis.

The definition of this technology in the example model's configuration looks as follows:

```
pv:
    essentials:
        name: 'Solar photovoltaic power'
        color: '#F9D956'
        parent: supply_power_plus
    constraints:
        export_carrier: electricity
        resource: file=pv_resource.csv:per_area  # Already accounts for panel efficiency␣
↪- kWh/m2. Source: Renewables.ninja Solar PV Power - Version: 1.1 - License: https://
↪creativecommons.org/licenses/by-nc/4.0/ - Reference: https://doi.org/10.1016/j.energy.
↪2016.08.060
        resource_unit: energy_per_area
        parasitic_eff: 0.85 # inverter losses
```

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```
        energy_cap_max: 250
        resource_area_max: 1500
        force_resource: true
        resource_area_per_energy_cap: 7 # 7m2 of panels needed to fit 1kWp of panels
        lifetime: 25
    costs:
        monetary:
            interest_rate: 0.10
            energy_cap: 1350
```

Finally, the parent of the PV technology is not `supply_plus`, but rather `supply_power_plus`. We use this to show the possibility of an intermediate technology group, which provides the information on the energy carrier (`electricity`) and the ultimate abstract base technology (`supply_plus`):

```
tech_groups:
    supply_power_plus:
        essentials:
            parent: supply_plus
            carrier: electricity
```

Intermediate technology groups allow us to avoid repetition of technology information, be it in `essentials`, `constraints`, or `costs`, by linking multiple technologies to the same intermediate group.

Conversion technologies

The example model defines two conversion technologies.

The first is `boiler` (natural gas boiler), which serves as an example of a simple conversion technology with one input carrier and one output carrier. Its only constraints are the cost of built capacity (`costs.monetary.energy_cap`), a constraint on its maximum built capacity (`constraints.energy_cap.max`), and an energy conversion efficiency (`energy_eff`).

Fig. 10: The layout of a simple node, in this case `boiler`, which has one carrier input, one carrier output, a carrier conversion efficiency ($energy_{eff}$), and a constraint on its maximum built $energy_{cap}$ (which puts an upper limit on $carrier_{prod}$).

The definition of this technology in the example model's configuration looks as follows:

```
boiler:
    essentials:
        name: 'Natural gas boiler'
        color: '#8E2999'
        parent: conversion
        carrier_out: heat
        carrier_in: gas
    constraints:
        energy_cap_max: 600
        energy_eff: 0.85
        lifetime: 25
    costs:
        monetary:
```

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```
            interest_rate: 0.10
            om_con: 0.004  # .4p/kWh
```

There are a few things to note. First, `boiler` defines a name, a color (given as an HTML color code), and a stack_weight. These are used by the built-in analysis tools when analyzing model results. Second, it specifies its parent, `conversion`, its carrier_in `gas`, and its carrier_out `heat`, thus setting itself up as a gas to heat conversion technology. This is followed by the definition of constraints and costs (the only cost class used is monetary, but this is where other "costs", such as emissions, could be defined).

The second technology is `chp` (combined heat and power), and serves as an example of a possible conversion_plus technology making use of two output carriers.

Fig. 11: The layout of a more complex node, in this case `chp`, which makes use of multiple output carriers.

This definition in the example model's configuration is more verbose:

```
chp:
    essentials:
        name: 'Combined heat and power'
        color: '#E4AB97'
        parent: conversion_plus
        primary_carrier_out: electricity
        carrier_in: gas
        carrier_out: electricity
        carrier_out_2: heat
    constraints:
        export_carrier: electricity
        energy_cap_max: 1500
        energy_eff: 0.405
        carrier_ratios.carrier_out_2.heat: 0.8
        lifetime: 25
    costs:
        monetary:
            interest_rate: 0.10
            energy_cap: 750
            om_prod: 0.004  # .4p/kWh for 4500 operating hours/year
            export: file=export_power.csv
```

See also:

The conversion_plus tech

Again, `chp` has the definitions for name, color, parent, and carrier_in/out. It now has an additional carrier (`carrier_out_2`) defined in its essential information, allowing a second carrier to be produced *at the same time* as the first carrier (`carrier_out`). The carrier ratio constraint tells us the ratio of carrier_out_2 to carrier_out that we can achieve, in this case 0.8 units of heat are produced every time a unit of electricity is produced. to produce these units of energy, gas is consumed at a rate of `carrier_prod(carrier_out) / energy_eff`, so gas consumption is only a function of power output.

As with the `pv`, the `chp` an export eletricity. The revenue gained from this export is given in the file `export_power.csv`, in which negative values are given per time step.

Demand technologies

Electricity and heat demand are defined here:

```
demand_electricity:
    essentials:
        name: 'Electrical demand'
        color: '#072486'
        parent: demand
        carrier: electricity

demand_heat:
    essentials:
        name: 'Heat demand'
        color: '#660507'
        parent: demand
        carrier: heat
```

Electricity and heat demand are technologies like any other. We will associate an actual demand time series with each demand technology later.

Transmission technologies

In this district, electricity and heat can be distributed between locations. Gas is made available in each location without consideration of transmission.

Fig. 12: A simple transmission node with an $energy_{eff}$.

```
power_lines:
    essentials:
        name: 'Electrical power distribution'
        color: '#6783E3'
        parent: transmission
        carrier: electricity
    constraints:
        energy_cap_max: 2000
        energy_eff: 0.98
        lifetime: 25
    costs:
        monetary:
            interest_rate: 0.10
            energy_cap_per_distance: 0.01

heat_pipes:
    essentials:
        name: 'District heat distribution'
        color: '#823739'
        parent: transmission
        carrier: heat
    constraints:
        energy_cap_max: 2000
```

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```
        energy_eff_per_distance: 0.975
        lifetime: 25
    costs:
        monetary:
            interest_rate: 0.10
            energy_cap_per_distance: 0.3
```

`power_lines` has an efficiency of 0.95, so a loss during transmission of 0.05. `heat_pipes` has a loss rate per unit distance of 2.5%/unit distance (or `energy_eff_per_distance` of 97.5%). Over the distance between the two locations of 0.5km (0.5 units of distance), this translates to $2.5^{0.5}$ = 1.58% loss rate.

Locations

In order to translate the model requirements shown in this section's introduction into a model definition, four locations are used: `X1`, `X2`, `X3`, and `N1`.

The technologies are set up in these locations as follows:

Fig. 13: Locations and their technologies in the urban-scale example model

Let's now look at the first location definition:

```
X1:
    techs:
        chp:
        pv:
        supply_grid_power:
            costs.monetary.energy_cap: 100 # cost of transformers
        supply_gas:
        demand_electricity:
            constraints.resource: file=demand_power.csv
        demand_heat:
            constraints.resource: file=demand_heat.csv
    available_area: 500
    coordinates: {x: 2, y: 7}
```

There are several things to note here:

- The location specifies a dictionary of technologies that it allows (`techs`), with each key of the dictionary referring to the name of technologies defined in our `techs.yaml` file. Note that technologies listed here must have been defined elsewhere in the model configuration.
- It also overrides some options for both `demand_electricity`, `demand_heat`, and `supply_grid_power`. For the latter, it simply sets a location-specific cost. For demands, the options set here are related to reading the demand time series from a CSV file. CSV is a simple text-based format that stores tables by comma-separated rows. Note that we did not define any `resource` option in the definition of these demands. Instead, this is done directly via a location-specific override. For this location, the files `demand_heat.csv` and `demand_power.csv` are loaded. As no column is specified (see *national scale example model*) Calliope will assume that the column name matches the location name `X1`. Note that in Calliope, a supply is positive and a demand is negative, so the stored CSV data will be negative.
- Coordinates are defined by cartesian coordinates `x` and `y`, which will be used to calculate distance of transmission lines (unless we specify otherwise later on) and for location-based visualisation. These coordinates are abstract,

unlike latitude and longitude, and can be used when we don't know (or care) about the geographical location of our problem.

- An `available_area` is defined, which will limit the maximum area of all `resource_area` technologies to the e.g. roof space available at our location. In this case, we just have `pv`, but the case where solar thermal panels compete with photovoltaic panels for space, this would the sum of the two to the available area.

The remaining location definitions look like this:

```
X2:
    techs:
        boiler:
            costs.monetary.energy_cap: 43.1 # different boiler costs
        pv:
            costs.monetary:
                    om_prod: -0.0203 # revenue for just producing electricity
                    export: -0.0491 # FIT return for PV export
        supply_gas:
        demand_electricity:
            constraints.resource: file=demand_power.csv
        demand_heat:
            constraints.resource: file=demand_heat.csv
    available_area: 1300
    coordinates: {x: 8, y: 7}

X3:
    techs:
        boiler:
            costs.monetary.energy_cap: 78 # different boiler costs
        pv:
            constraints:
                energy_cap_max: 50 # changing tariff structure below 50kW
            costs.monetary:
                    om_annual: -80.5 # reimbursement per kWp from FIT
        supply_gas:
        demand_electricity:
            constraints.resource: file=demand_power.csv
        demand_heat:
            constraints.resource: file=demand_heat.csv
    available_area: 900
    coordinates: {x: 5, y: 3}
```

`X2` and `X3` are very similar to `X1`, except that they do not connect to the national electricity grid, nor do they contain the `chp` technology. Specific `pv` cost structures are also given, emulating e.g. commercial vs. domestic feed-in tariffs.

`N1` differs to the others by virtue of containing no technologies. It acts as a branching station for the heat network, allowing connections to one or both of `X2` and `X3` without double counting the pipeline from `X1` to `N1`. Its definition look like this:

```
N1: # location for branching heat transmission network
    coordinates: {x: 5, y: 7}
```

For transmission technologies, the model also needs to know which locations can be linked, and this is set up in the model configuration as follows:

```
X1,X2:
    techs:
        power_lines:
            distance: 10
X1,X3:
    techs:
        power_lines:
X1,N1:
    techs:
        heat_pipes:
N1,X2:
    techs:
        heat_pipes:
N1,X3:
    techs:
        heat_pipes:
```

The distance measure for the power line is larger than the straight line distance given by the coordinates of `X1` and `X2`, so we can provide more information on non-direct routes for our distribution system. These distances will override any automatic straight-line distances calculated by coordinates.

Revenue by export

Defined for both PV and CHP, there is the option to accrue revenue in the system by exporting electricity. This export is considered as a removal of the energy carrier `electricity` from the system, in exchange for negative cost (i.e. revenue). To allow this, `carrier_export: electricity` has been given under both technology definitions and an `export` value given under costs.

The revenue from PV export varies depending on location, emulating the different feed-in tariff structures in the UK for commercial and domestic properties. In domestic properties, the revenue is generated by simply having the installation (per kW installed capacity), as export is not metered. Export is metered in commercial properties, thus revenue is generated directly from export (per kWh exported). The revenue generated by CHP depends on the electricity grid wholesale price per kWh, being 80% of that. These revenue possibilities are reflected in the technologies' and locations' definitions.

Running the model

We now take you through running the model in a Jupyter notebook, which you can view here. After clicking on that link, you can also download and run the notebook yourself (you will need to have Calliope installed).

1.6.3 Tutorial 3: Mixed Integer Linear Programming

This example is based on the *urban scale example model*, but with an override. In the model's `scenarios.yaml` file overrides are defined which trigger binary and integer decision variables, creating a MILP model, rather than a conventional LP model.

Units

The capacity of a technology is usually a continuous decision variable, which can be within the range of 0 and `energy_cap_max` (the maximum capacity of a technology). In this model, we introduce a unit limit on the CHP instead:

```
    chp:
        constraints:
            units_max: 4
            energy_cap_per_unit: 300
            energy_cap_min_use: 0.2
        costs:
            monetary:
                energy_cap: 700
                purchase: 40000
```

A unit maximum allows a discrete, integer number of CHP to be purchased, each having a capacity of `energy_cap_per_unit`. Any of `energy_cap_max`, `energy_cap_min`, or `energy_cap_equals` are now ignored, in favour of `units_max`, `units_min`, or `units_equals`. A useful feature unlocked by introducing this is the ability to set a minimum operating capacity which is *only* enforced when the technology is operating. In the LP model, `energy_cap_min_use` would force the technology to operate at least at that proportion of its maximum capacity at each time step. In this model, the newly introduced `energy_cap_min_use` of 0.2 will ensure that the output of the CHP is 20% of its maximum capacity in any time step in which it has a non-zero output.

Purchase cost

The boiler does not have a unit limit, it still utilises the continuous variable for its capacity. However, we have introduced a `purchase` cost:

```
    boiler:
        costs:
            monetary:
                energy_cap: 35
                purchase: 2000
```

By introducing this, the boiler now has a binary decision variable associated with it, which is 1 if the boiler has a non-zero `energy_cap` (i.e. the optimisation results in investment in a boiler) and 0 if the capacity is 0. The purchase cost is applied to the binary result, providing a fixed cost on purchase of the technology, irrespective of the technology size. In physical terms, this may be associated with the cost of pipework, land purchase, etc. The purchase cost is also imposed on the CHP, which is applied to the number of integer CHP units in which the solver chooses to invest.

MILP functionality can be easily applied, but convergence is slower as a result of integer/binary variables. It is recommended to use a commercial solver (e.g. Gurobi, CPLEX) if you wish to utilise these variables outside this example model.

Asynchronous energy production/consumption

The heat pipes which distribute thermal energy in the network may be prone to dissipating heat in an unphysical way. I.e. given that they have distribution losses associated with them, in any given timestep, a link could produce and consume energy in the same timestep, losing energy to the atmosphere in both instances, but having a net energy transmission of zero. This allows e.g. a CHP facility to overproduce heat to produce more cheap electricity, and have some way of dumping that heat. The `asynchronous_prod_con` binary constraint ensures this phenomenon is avoided:

```
    heat_pipes:
        constraints:
            force_asynchronous_prod_con: true
```

Now, only one of `carrier_prod` and `carrier_con` can be non-zero in a given timestep. This constraint can also be applied to storage technologies, to similarly control charge/discharge.

Running the model

We now take you through running the model in a Jupyter notebook, which you can view here. After clicking on that link, you can also download and run the notebook yourself (you will need to have Calliope installed).

1.7 Advanced constraints

This section, as the title suggests, contains more info and more details, and in particular, information on some of Calliope's more advanced functionality.

We suggest you read the *Building a model*, *Running a model* and *Analysing a model* sections first.

1.7.1 The `supply_plus` tech

The `plus` tech groups offer complex functionality, for technologies which cannot be described easily. `Supply_plus` allows a supply technology with internal storage of resource before conversion to the carrier happens. This could be emulated with dummy carriers and a combination of supply, storage, and conversion techs, but the `supply_plus` tech allows for concise and mathematically more efficient formulation.

Fig. 14: Representation of the `supply_plus` technology

An example use of `supply_plus` is to define a concentrating solar power (CSP) technology which consumes a solar resource, has built-in thermal storage, and produces electricity. See the *national-scale built-in example model* for an application of this.

See the *listing of supply_plus configuration* in the abstract base tech group definitions for the additional constraints that are possible.

Warning: When analysing results from supply_plus, care must be taken to correctly account for the losses along the transformation from resource to carrier. For example, charging of storage from the resource may have a `resource_eff`-associated loss with it, while discharging storage to produce the carrier may have a different loss resulting from a combination of `energy_eff` and `parasitic_eff`. Such intermediate conversion losses need to be kept in mind when comparing discharge from storage with `carrier_prod` in the same time step.

1.7.2 The conversion_plus tech

The plus tech groups offer complex functionality, for technologies which cannot be described easily. Conversion_plus allows several carriers to be converted to several other carriers. Describing such a technology requires that the user understands the carrier_ratios, i.e. the interactions and relative efficiencies of carrier inputs and outputs.

Fig. 15: Representation of the most complex conversion_plus technology available

The conversion_plus technologies allows for up to three **carrier groups** as inputs (carrier_in, carrier_in_2 and carrier_in_3) and up to three carrier groups as outputs (carrier_out, carrier_out_2 and carrier_out_3). A carrier group can contain any number of carriers.

The efficiency of a conversion_plus tech dictates how many units of *carrier_out* are produced per unit of consumed *carrier_in*. A unit of *carrier_out_2* and of *carrier_out_3* is produced each time a unit of *carrier_out* is produced. Similarly, a unit of *Carrier_in_2* and of *carrier_in_3* is consumed each time a unit of *carrier_in* is consumed. Within a given carrier group (e.g. *carrier_out_2*) any number of carriers can meet this one unit. The carrier_ratio of any carrier compares it either to the production of one unit of *carrier_out* or to the consumption of one unit of *carrier_in*.

In this section, we give examples of a few conversion_plus technologies alongside the YAML formulation required to construct them:

Combined heat and power

A combined heat and power plant produces electricity, in this case from natural gas. Waste heat that is produced can be used to meet nearby heat demand (e.g. via district heating network). For every unit of electricity produced, 0.8 units of heat are always produced. This is analogous to the heat to power ratio (HTP). Here, the HTP is 0.8.

```
chp:
    essentials:
        name: Combined heat and power
        carrier_in: gas
        carrier_out: electricity
        carrier_out_2: heat
        primary_carrier_out: electricity
    constraints:
        energy_eff: 0.45
        energy_cap_max: 100
        carrier_ratios.carrier_out_2.heat: 0.8
```

Air source heat pump

The output energy from the heat pump can be *either* heat or cooling, simulating a heat pump that can be useful in both summer and winter. For each unit of electricity input, one unit of output is produced. Within this one unit of carrier_out, there can be a combination of heat and cooling. Heat is produced with a COP of 5, cooling with a COP of 3. If only heat were produced in a timestep, 5 units of it would be available in carrier_out; similarly 3 units for cooling. In another timestep, both heat and cooling might be produced with e.g. 2.5 units heat + 1.5 units cooling = 1 unit of carrier_out.

```
ahp:
    essentials:
        name: Air source heat pump
        carrier_in: electricity
        carrier_out: [heat, cooling]
        primary_carrier_out: heat

    constraints:
        energy_eff: 1
        energy_cap_max: 100
        carrier_ratios:
            carrier_out:
                heat: 5
                cooling: 3
```

Combined cooling, heat and power (CCHP)

A CCHP plant can use generated heat to produce cooling via an absorption chiller. As with the CHP plant, electricity is produced at 45% efficiency. For every unit of electricity produced, 1 unit of `carrier_out_2` must be produced, which can be a combination of 0.8 units of heat and 0.5 units of cooling. Some example ways in which the model could decide to operate this unit in a given time step are:

- 1 unit of gas (`carrier_in`) is converted to 0.45 units of electricity (`carrier_out`) and (0.8 * 0.45) units of heat (`carrier_out_2`)
- 1 unit of gas is converted to 0.45 units electricity and (0.5 * 0.45) units of cooling
- 1 unit of gas is converted to 0.45 units electricity, (0.3 * 0.8 * 0.45) units of heat, and (0.7 * 0.5 * 0.45) units of cooling

```
cchp:
    essentials:
        name: Combined cooling, heat and power
        carrier_in: gas
        carrier_out: electricity
        carrier_out_2: [heat, cooling]
        primary_carrier_out: electricity

    constraints:
        energy_eff: 0.45
        energy_cap_max: 100
        carrier_ratios.carrier_out_2: {heat: 0.8, cooling: 0.5}
```

Advanced gas turbine

This technology can choose to burn methane (CH:sub:*4*) or send hydrogen (H:sub:*2*) through a fuel cell to produce electricity. One unit of carrier_in can be met by any combination of methane and hydrogen. If all methane, 0.5 units of carrier_out would be produced for 1 unit of carrier_in (energy_eff). If all hydrogen, 0.25 units of carrier_out would be produced for the same amount of carrier_in (energy_eff * hydrogen carrier ratio).

```
gt:
    essentials:
        name: Advanced gas turbine
        carrier_in: [methane, hydrogen]
        carrier_out: electricity

    constraints:
        energy_eff: 0.5
        energy_cap_max: 100
        carrier_ratios:
            carrier_in: {methane: 1, hydrogen: 0.5}
```

Complex fictional technology

There are few instances where using the full capacity of a conversion_plus tech is physically possible. Here, we have a fictional technology that combines fossil fuels with biomass/waste to produce heat, cooling, and electricity. Different 'grades' of heat can be produced, the higher grades having an alternative. High grade heat (`high_T_heat`) is produced and can be used directly, or used to produce electricity (via e.g. organic rankine cycle). `carrier_out` is thus a combination of these two. *carrier_out_2* can be 0.3 units mid grade heat for every unit *carrier_out* or 0.2 units cooling. Finally, 0.1 units `carrier_out_3`, low grade heat, is produced for every unit of *carrier_out*.

```
complex:
    essentials:
        name: Complex fictional technology
        carrier_in: [coal, gas, oil]
        carrier_in_2: [biomass, waste]
        carrier_out: [high_T_heat, electricity]
        carrier_out_2: [mid_T_heat, cooling]
        carrier_out_3: low_T_heat
        primary_carrier_out: electricity

    constraints:
        energy_eff: 1
        energy_cap_max: 100
        carrier_ratios:
            carrier_in: {coal: 1.2, gas: 1, oil: 1.6}
            carrier_in_2: {biomass: 1, waste: 1.25}
            carrier_out: {high_T_heat: 0.8, electricity: 0.6}
            carrier_out_2: {mid_T_heat: 0.3, cooling: 0.2}
            carrier_out_3.low_T_heat: 0.15
```

A `primary_carrier_out` must be defined when there are multiple `carrier_out` values defined, similarly `primary_carrier_in` can be defined for `carrier_in`. *primary_carriers* can be defined as any carrier in a tech-

nology's input/output carriers (including secondary and tertiary carriers). The chosen output carrier will be the one to which production costs are applied (reciprocally, input carrier for consumption costs).

Note: `Conversion_plus` technologies can also export any one of their output carriers, by specifying that carrier as `carrier_export`.

1.7.3 Resource area constraints

Several optional constraints can be used to specify area-related restrictions on technology use.

To make use of these constraints, one should set `resource_unit: energy_per_area` for the given technologies. This scales the available resource at a given location for a given technology with its `resource_area` decision variable.

The following related settings are available:

- `resource_area_equals`, `resource_area_max`, `resource_area_min`: Set uppper or lower bounds on resource_area or force it to a specific value
- `resource_area_per_energy_cap`: False by default, but if set to true, it forces `resource_area` to follow `energy_cap` with the given numerical ratio (e.g. setting to 1.5 means that `resource_area == 1.5 * energy_cap`)

By default, `resource_area_max` is infinite and `resource_area_min` is 0 (zero).

1.7.4 Group constraints

Group constraints are applied to named sets of locations and techs, called "constraint groups", specified through a top-level `group_constraints` key (sitting alongside other top-level keys like `model` and `run`).

The below example shows two such named groups. The first does not specify a subset of techs or locations and is thus applied across the entire model. In the example, we use `cost_max` with the `co2` cost class to specify a model-wide emissions limit (assuming the technologies in the model have `co2` costs associated with them). We also use the `demand_share_min` constraint to force wind and PV to supply at least 40% of electricity demand in Germany, which is modelled as two locations (North and South):

```
run:
    ...

model:
    ...

group_constraints:
    # A constraint group to apply a systemwide CO2 cap
    systemwide_co2_cap:
        cost_max:
            co2: 100000
    # A constraint group to enforce renewable generation in Germany
    renewable_minimum_share_in_germany:
        techs: ['wind', 'pv']
        locs: ['germany_north', 'germany_south']
        demand_share_min:
            electricity: 0.4
```

When specifying group constraints, a named group must give at least one constraint, but can list an arbitrary amount of constraints, and optionally give a subset of techs and locations:

```
group_constraints:
    group_name:
        techs: []  # Optional, can be left out if empty
        locs: []  # Optional, can be left out if empty
        # Any number of constraints can be specified for the given group
        constraint_1: ...
        constraint_2: ...
        ...
```

The below table lists all available group constraints.

Note that when computing the share for `demand_share` constraints, only `demand` technologies are counted, and that when computing the share for `supply_share` constraints, `supply` and `supply_plus` technologies are counted.

Table 1: Group constraints

Constraint	Dimensions	Description
demand_share_min	carriers	Minimum share of carrier demand met from a set of technologies across a set of locations, on average over the entire model period.
demand_share_max	carriers	Maximum share of carrier demand met from a set of technologies across a set of locations, on average over the entire model period.
demand_share_equals	carriers	Share of carrier demand met from a set of technologies across a set of locations, on average over the entire model period.
demand_share_per_timestep_min	carriers	Minimum share of carrier demand met from a set of technologies across a set of locations, in each individual timestep.
demand_share_per_timestep_max	carriers	Maximum share of carrier demand met from a set of technologies across a set of locations, in each individual timestep.
demand_share_per_timestep_equals	carriers	Share of carrier demand met from a set of technologies across a set of locations, in each individual timestep.
demand_share_per_timestep_decision	carriers	Turn the per-timestep share of carrier demand met from a set of technologies across a set of locations into a model decision variable.
carrier_prod_share_min	carriers	Minimum share of carrier production met from a set of technologies across a set of locations, on average over the entire model period.
carrier_prod_share_max	carriers	Maximum share of carrier production met from a set of technologies across a set of locations, on average over the entire model period.
carrier_prod_share_equals	carriers	Share of carrier production met from a set of technologies across a set of locations, on average over the entire model period.
carrier_prod_share_per_timestep_min	carriers	Minimum share of carrier production met from a set of technologies across a set of locations, in each individual timestep.
carrier_prod_share_per_timestep_max	carriers	Maximum share of carrier production met from a set of technologies across a set of locations, in each individual timestep.
carrier_prod_share_per_timestep_equals	carriers	Share of carrier production met from a set of technologies across a set of locations, in each individual timestep.
net_import_share_min	carriers	Minimum share of demand met from transmission technologies into a set of locations, on average over the entire model period. All transmission technologies of the chosen carrier are added automatically and technologies must thus not be defined explicitly.
net_import_share_max	carriers	Maximum share of demand met from transmission technologies into a set of locations, on average over the entire model period. All transmission technologies of the chosen carrier are added automatically and technologies must thus not be defined explicitly.

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Table 1 – continued from previous page

Constraint	Dimensions	Description
net_import_share_equals	carriers	Share of demand met from transmission technologies into a set of locations, on average over the entire model. All transmission technologies of the chosen carrier are added automatically and technologies must thus not be defined explicitly. period.
carrier_prod_min	carriers	Minimum absolute sum of supplied energy (*carrier_prod*) over all timesteps for a set of technologies across a set of locations.
carrier_prod_max	carriers	Maximum absolute sum of supplied energy (*carrier_prod*) over all timesteps for a set of technologies across a set of locations.
carrier_prod_equals	carriers	Exact absolute sum of supplied energy (*carrier_prod*) over all timesteps for a set of technologies across a set of locations.
carrier_con_min	carriers	Minimum sum of consumed energy (*carrier_con*) over all timesteps for a set of conversion/demand technologies across a set of locations. Values are negative and are relative to zero, i.e. a minimum value of -1 means that consumed energy must be < -1
carrier_con_max	carriers	Maximum sum of consumed energy (*carrier_con*) over all timesteps for a set of conversion/demand technologies across a set of locations. Values are negative and are relative to zero, i.e. a maximum value of -1 means that consumed energy must be > -1
carrier_con_equals	carriers	Exact sum of consumed energy (*carrier_con*) over all timesteps for a set of conversion/demand technologies across a set of locations. Values are negative.
cost_max	costs	Maximum total cost from a set of technologies across a set of locations.
cost_min	costs	Minimum total cost from a set of technologies across a set of locations.
cost_equals	costs	Total cost from a set of technologies across a set of locations must equal given value.
cost_var_max	costs	Maximum variable cost from a set of technologies across a set of locations.
cost_var_min	costs	Minimum variable cost from a set of technologies across a set of locations.
cost_var_equals	costs	Variable cost from a set of technologies across a set of locations must equal given value.
cost_investment_max	costs	Maximum investment cost from a set of technologies across a set of locations.
cost_investment_min	costs	Minimum investment cost from a set of technologies across a set of locations.
cost_investment_equals	costs	Investment cost from a set of technologies across a set of locations must equal given value.
energy_cap_share_min	–	Minimum share of installed capacity from a set of technologies across a set of locations.
energy_cap_share_max	–	Maximum share of installed capacity from a set of technologies across a set of locations.
energy_cap_share_equals	–	Exact share of installed capacity from a set of technologies across a set of locations.
energy_cap_min	–	Minimum installed capacity from a set of technologies across a set of locations.
energy_cap_max	–	Maximum installed capacity from a set of technologies across a set of locations.
energy_cap_equals	–	Exact installed capacity from a set of technologies across a set of locations.
resource_area_min	–	Minimum resource area used by a set of technologies across a set of locations.
resource_area_max	–	Maximum resource area used by a set of technologies across a set of locations.
resource_area_equals	–	Exact resource area used by a set of technologies across a set of locations.

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Table 1 – continued from previous page

Constraint	Dimensions	Description
`storage_cap_min`	–	Minimum installed storage capacity from a set of technologies across a set of locations.
`storage_cap_max`	–	Maximum installed storage capacity from a set of technologies across a set of locations.
`storage_cap_equals`		Exact installed storage capacity from a set of technologies across a set of locations.

For specifics of the mathematical formulation of the available group constraints, see *Group constraints* in the mathematical formulation section.

See also:

The *built-in national-scale example*'s `scenarios.yaml` shows two example uses of group constraints: limiting shared capacity with `energy_cap_max` and enforcing a minimum shared power generation with `carrier_prod_share_min`.

`demand_share_per_timestep_decision`

The `demand_share_per_timestep_decision` constraint is a special case amongst group constraints, as it introduces a new decision variable, allowing the model to set the share of demand met by each technology given in the constraint's group, across the locations given in the group. The fraction set in the constraint is the fraction of total demand over which the model has control. Setting this to anything else than `1.0` only makes sense when a subset of technologies is targeted by the constraint.

It can also be set to `.inf` to permit Calliope to decide on the fraction of total demand to cover by the constraint. This can be necessary in cases where there are sources of carrier consumption other than demand in the locations covered by the group constraint: when using conversion techs or when there are losses from storage and transmission, as the share may then be higher than 1, leading to an infeasible model if it is forced to `1.0`.

This constraint can be useful in large-scale models where individual technologies should not fluctuate in their relative share from time step to time step, for example, when modelling the relative share of heating demand from different heating technologies.

Note: In some model setups, numerical issues in the solving process can cause model infeasibility due to this group constraint. It may therefore be necessary to 'relax' this constraint, such that the requirement for a technology to have a specific demand share in each timestep is relax by a few percent. To enfore this relaxation, you can set the run configuration option `run.relax_constraint.demand_share_per_timestep_decision_main_constraint` to something other than `0` (default). E.g. a value of 0.01 will set a 1% relaxation (`lhs == rhs -> lhs >= 0.99 * rhs & lhs <= 1.01 * rhs`).

Warning: It is easy to create an infeasible model by setting several conflicting group constraints, in particular when `demand_share_per_timestep_decision` is involved. Make sure you think through the implications when setting up these constraints!

1.7.5 Per-distance constraints and costs

Transmission technologies can additionally specify per-distance efficiency (loss) with `energy_eff_per_distance` and per-distance costs with `energy_cap_per_distance`:

```
techs:
    my_transmission_tech:
        essentials:
            ...
        constraints:
            # "efficiency" (1-loss) per unit of distance
            energy_eff_per_distance: 0.99
        costs:
            monetary:
                # cost per unit of distance
                energy_cap_per_distance: 10
```

The distance is specified in transmission links:

```
links:
    location1,location2:
        my_transmission_tech:
            distance: 500
            constraints:
                energy_cap.max: 10000
```

If no distance is given, but the locations have been given lat and lon coordinates, Calliope will compute distances automatically (based on the length of a straight line connecting the locations).

1.7.6 One-way transmission links

Transmission links are bidirectional by default. To force unidirectionality for a given technology along a given link, you have to set the `one_way` constraint in the constraint definition of that technology, for that link:

```
links:
    location1,location2:
        transmission-tech:
            constraints:
                one_way: true
```

This will only allow transmission from `location1` to `location2`. To swap the direction, the link name must be inverted, i.e. `location2,location1`.

1.7.7 Cyclic storage

With `storage` and `supply_plus` techs, it is possible to link the storage at either end of the timeseries, using cyclic storage. This allows the user to better represent multiple years by just modelling one year. Cyclic storage is activated by default (to deactivate: `run.cyclic_storage: false`). As a result, a technology's initial stored energy at a given location will be equal to its stored energy at the end of the model's last timestep.

For example, for a model running over a full year at hourly resolution, the initial storage at *Jan 1st 00:00:00* will be forced equal to the storage at the end of the timestep *Dec 31st 23:00:00*. By setting `storage_initial` for a

technology, it is also possible to fix the value in the last timestep. For instance, with `run.cyclic_storage: true` and a `storage_initial` of zero, the stored energy *must* be zero by the end of the time horizon.

Without cyclic storage in place (as was the case prior to v0.6.2), the storage tech can have any amount of stored energy by the end of the timeseries. This may prove useful in some cases, but has less physical meaning than assuming cyclic storage.

Note: Cyclic storage also functions when time clustering, if allowing storage to be tracked between clusters (see *Time resolution adjustment*). However, it cannot be used in `operate` run mode.

1.7.8 Revenue and export

It is possible to specify revenues for technologies simply by setting a negative cost value. For example, to consider a feed-in tariff for PV generation, it could be given a negative operational cost equal to the real operational cost minus the level of feed-in tariff received.

Export is an extension of this, allowing an energy carrier to be removed from the system without meeting demand. This is analogous to e.g. domestic PV technologies being able to export excess electricity to the national grid. A cost (or negative cost: revenue) can then be applied to export.

Note: Negative costs can be applied to capacity costs, but the user must an ensure a capacity limit has been set. Otherwise, optimisation will be unbounded.

1.7.9 The `group_share` constraint (deprecated)

Warning: `group_share` is deprecated as of v0.6.4 and will be removed in v0.7.0. Use the new, more flexible functionality *Group constraints* to replace it.

The `group_share` constraint can be used to force groups of technologies to fulfill certain shares of supply or capacity.

For example, assuming a model containing a `csp` and a `cold_fusion` power generation technology, we could force at least 85% of power generation in the model to come from these two technologies with the following constraint definition in the `model` settings:

```
model:
    group_share:
        csp,cold_fusion:
            carrier_prod_min:
                power: 0.85
```

Possible `group_share` constraints with carrier-specific settings are:

- `carrier_prod_min`
- `carrier_prod_max`
- `carrier_prod_equals`

Possible `group_share` constraints with carrier-independent settings are:

- `energy_cap_min`

- energy_cap_max
- energy_cap_equals

These can be implemented as, for example, to force at most 20% of energy_cap to come from the two listed technologies:

```
model:
    group_share:
        csp,cold_fusion:
            energy_cap_max: 0.20
```

1.7.10 Binary and mixed-integer constraints

Calliope models are purely linear by default. However, several constraints can turn a model into a binary or mixed-integer model. Because solving problems with binary or integer variables takes considerably longer than solving purely linear models, it usually makes sense to carefully consider whether the research question really necessitates going beyond a purely linear model.

By applying a purchase cost to a technology, that technology will have a binary variable associated with it, describing whether or not it has been "purchased".

By applying units.max, units.min, or units.equals to a technology, that technology will have a integer variable associated with it, describing how many of that technology have been "purchased". If a purchase cost has been applied to this same technology, the purchasing cost will be applied per unit.

Warning: Integer and binary variables are a recent addition to Calliope and may not cover all edge cases as intended. Please raise an issue on GitHub if you see unexpected behavior.

See also:

Tutorial 3: Mixed Integer Linear Programming

Asynchronous energy production/consumption

The asynchronous_prod_con binary constraint ensures that only one of carrier_prod and carrier_con can be non-zero in a given timestep.

This constraint can be applied to storage or transmission technologies. This example shows use with a heat transmission technology:

```
    heat_pipes:
        constraints:
            force_asynchronous_prod_con: true
```

In the above example, heat pipes which distribute thermal energy in the network may be prone to dissipating heat in an unphysical way. I.e. given that they have distribution losses associated with them, in any given timestep, a link could produce and consume energy in the same timestep, losing energy to the atmosphere in both instances, but having a net energy transmission of zero. This might allow e.g. a CHP facility to overproduce heat to produce more cheap electricity, and have some way of dumping that heat. Enabling the asynchronous_prod_con constraint ensures that this does not happen.

1.7.11 User-defined custom constraints

It is possible to pass custom constraints to the Pyomo backend, using the *backend interface*. This requires an understanding of the structure of Pyomo constraints. As an example, the following code reproduces the constraint which limits the maximum carrier consumption to less than or equal to the technology capacity:

```
model = calliope.Model(...)
model.run()  # or `model.run(build_only=True)` if you don't want the model to be␣
↪optimised before adding the new constraint

constraint_name = 'max_capacity_90_constraint'
constraint_sets = ['loc_techs_supply']

def max_capacity_90_constraint_rule(backend_model, loc_tech):

    return backend_model.energy_cap[loc_tech] <= (
        backend_model.energy_cap_max[loc_tech] * 0.9
    )

# Add the constraint
model.backend.add_constraint(constraint_name, constraint_sets, max_capacity_90_
↪constraint_rule)

# Rerun the model with new constraint.
new_model = model.backend.rerun()  # `new_model` is a calliope model *without* a backend,␣
↪it is only useful for saving the results to file
```

Note:

- We like the convention that constraint names end with 'constraint' and constraint rules have the same text, with an appended '_rule', but you are not required to follow this convention to have a working constraint.
- `model.run(force_rerun=True)` will *not* implement the new constraint, `model.backend.rerun()` is required. If you run `model.run(force_rerun=True)`, the backend model will be rebuilt, killing any changes you've made.

1.8 Advanced features

Once you're comfortable with *building*, *running*, and *analysing* one of the built-in example models, you may want to explore Calliope's advanced functionality. With these features, you will be able to build and run complex models in no time.

1.8.1 Time resolution adjustment

Models have a default timestep length (defined implicitly by the timesteps of the model's time series data). This default resolution can be adjusted over parts of the dataset by specifying time resolution adjustment in the model configuration, for example:

```
model:
    time:
        function: resample
        function_options: {'resolution': '6H'}
```

In the above example, this would resample all time series data to 6-hourly timesteps.

Calliope's time resolution adjustment functionality allows running a function that can perform arbitrary adjustments to the time series data in the model.

The available options include:

1. Uniform time resolution reduction through the `resample` function, which takes a pandas-compatible rule describing the target resolution (see above example).
2. Deriving representative days from the input time series, by applying the clustering method implemented in *calliope.time.clustering*, for example:

```
model:
    time:
        function: apply_clustering
        function_options:
            clustering_func: kmeans
            how: mean
            k: 20
```

When using representative days, a number of additional constraints are added, based on the study undertaken by Kotzur et al. These constraints require a new decision variable `storage_inter_cluster`, which tracks storage between all the dates of the original timeseries. This particular functionality can be disabled by including `storage_inter_cluster: false` in the *function_options* given above.

Note: It is also possible to load user-defined representative days, by pointing to a file in *clustering_func* in the same format as pointing to timeseries files in constraints, e.g. `clustering_func: file=clusters.csv:column_name`. Clusters are unique per datestep, so the clustering file is most readable if the index is at datestep resolution. But, the clustering file index can be in timesteps (e.g. if sharing the same file as a constraint timeseries), with the cluster number repeated per timestep in a day. Cluster values should be integer, starting at zero.

---

3. Heuristic selection of time steps, that is, the application of one or more of the masks defined in *calliope.time.masks*, which will mark areas of the time series to retain at maximum resolution (unmasked) and areas where resolution can be lowered (masked). Options can be passed to the masking functions by specifying `options`. A `time.function` can still be specified and will be applied to the masked areas (i.e. those areas of the time series not selected to remain at the maximum resolution), as in this example, which looks for the week of minimum and maximum potential wind generation (assuming a `wind` technology was specified), then reduces the rest of the input time series to 6-hourly resolution:

```
model:
    time:
        masks:
            - {function: extreme, options: {padding: 'calendar_week', tech: 'wind', how:
↪'max'}}
```

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```
            - {function: extreme, options: {padding: 'calendar_week', tech: 'wind', how:
↪'min'}}
        function: resample
        function_options: {'resolution': '6H'}
```

Warning: When using time clustering or time masking, the resulting timesteps will be assigned different weights depending on how long a period of time they represent. Weights are used for example to give appropriate weight to the operational costs of aggregated typical days in comparison to individual extreme days, if both exist in the same processed time series. The weighting is accessible in the model data, e.g. through `model.inputs.timestep_weights`. The interpretation of results when weights are not 1 for all timesteps requires caution. Production values are not scaled according to weights, but costs are multiplied by weight, in order to weight different timesteps appropriately in the objective function. This means that costs and production values are not consistent without manually post-processing them by either multipyling production by weight (production would then be inconsistent with capacity) or dividing costs by weight. The computation of levelised costs and of capacity factors takes weighting into account, so these values are consisten and can be used as usual.

See also:

See the implementation of constraints in `calliope.backend.pyomo.constraints` for more detail on timestep weights and how they affect model constraints.

1.8.2 Setting a random seed

By specifying `model.random_seed` in the model configuration, any alphanumeric string can be used to initialise the random number generator at the very start of model processing.

This is useful for full reproducibility of model results where time series clustering is used, as clustering methods such as k-means depend on randomly generated initial conditions.

Note that this affects only the random number generator used in Calliope's model preprocessing and not in any way the solver used to solve the model (any solver-specific options need to be set specifically for that solver; see *Specifying custom solver options*).

1.8.3 Using `tech_groups` to group configuration

In a large model, several very similar technologies may exist, for example, different kinds of PV technologies with slightly different cost data or with different potentials at different model locations.

To make it easier to specify closely related technologies, `tech_groups` can be used to specify configuration shared between multiple technologies. The technologies then give the `tech_group` as their parent, rather than one of the abstract base technologies.

You can as well extend abstract base technologies, by adding an attribute that will be in effect for all technologies derived from the base technology. To do so, use the name of the abstract base technology for your group, but omit the parent.

For example:

```
tech_groups:
    supply:
        constraints:
```

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```
            monetary:
                interest_rate: 0.1
    pv:
        essentials:
            parent: supply
            carrier: power
        constraints:
            resource: file=pv_resource.csv
            lifetime: 30
        costs:
            monetary:
                om_annual_investment_fraction: 0.05
                depreciation_rate: 0.15

techs:
    pv_large_scale:
        essentials:
            parent: pv
            name: 'Large-scale PV'
        constraints:
            energy_cap_max: 2000
        costs:
            monetary:
                energy_cap: 750
    pv_rooftop:
        essentials:
            parent: pv
            name: 'Rooftop PV'
        constraints:
            energy_cap_max: 10000
        costs:
            monetary:
                energy_cap: 1000
```

None of the `tech_groups` appear in model results, they are only used to group model configuration values.

1.8.4 Removing techs, locations and links

By specifying `exists: false` in the model configuration, which can be done for example through overrides, model components can be removed for debugging or scenario analysis.

This works for:

- Techs: `techs.tech_name.exists: false`
- Locations: `locations.location_name.exists: false`
- Links: `links.location1,location2.exists: false`
- Techs at a specific location: `locations.location_name.techs.tech_name.exists: false`
- Transmission techs at a specific location: `links.location1,location2.techs.transmission_tech.exists: false`
- Group constraints: `group_constraints.my_constraint.exists: false`

1.8.5 Operational mode

In planning mode, constraints are given as upper and lower boundaries and the model decides on an optimal system configuration. In operational mode, all capacity constraints are fixed and the system is operated with a receding horizon control algorithm.

To specify a runnable operational model, capacities for all technologies at all locations must have be defined. This can be done by specifying `energy_cap_equals`. In the absence of `energy_cap_equals`, constraints given as `energy_cap_max` are assumed to be fixed in operational mode.

Operational mode runs a model with a receding horizon control algorithm. This requires two additional settings:

```
run:
    operation:
        horizon: 48  # hours
        window: 24  # hours
```

`horizon` specifies how far into the future the control algorithm optimises in each iteration. `window` specifies how many of the hours within `horizon` are actually used. In the above example, decisions on how to operate for each 24-hour window are made by optimising over 48-hour horizons (i.e., the second half of each optimisation run is discarded). For this reason, `horizon` must always be larger than `window`.

1.8.6 SPORES mode

SPORES refers to Spatially-explicit Practically Optimal REsultS. This run mode allows a user to generate any number of alternative results which are within a certain range of the optimal cost. It follows on from previous work in the field of *modelling to generate alternatives* (MGA), with a particular emphasis on alternatives that vary maximally in the spatial dimension. This run mode was developed for and implemented in a study on the future Italian energy system. As an example, if you wanted to generate 10 SPORES, all of which are within 10% of the optimal system cost, you would define the following in your *run* configuration:

```
run.mode: spores
run.spores_options:
    spores_number: 10  # The number of SPORES to generate
    slack: 0.1  # The fraction above the cost-optimal cost to set the maximum cost␣
↪during SPORES
    score_cost_class: spores_score  # The cost class to optimise against when generating␣
↪SPORES
    slack_cost_group: systemwide_cost_max  # The group constraint name in which the␣
↪`cost_max` constraint is assigned, for use alongside the slack and cost-optimal cost
```

You will also need to manually set up some other parts of your model to deal with SPORES:

1. Set up a group constraint that can limit the total cost of your system to the SPORES cost (i.e. optimal + 10%). The initial value being infinite ensures it does not impinge on the initial cost-optimal run; the constraint will be adapted internally to set a new value which corresponds to the optimal cost plus the slack.

```
group_constraints:
    systemwide_cost_max.cost_max.monetary: .inf
```

2. Assign a *spores_score* cost to all technologies and locations that you want to limit within the scope of finding alternatives. The *spores_score* is the cost class against which the model optimises in the generation of SPORES: technologies at locations with higher scores will be penalised in the objective function, so are less likely to be chosen. In the National Scale example model, this looks like:

```
techs.ccgt.costs.spores_score.energy_cap: 0
techs.ccgt.costs.spores_score.interest_rate: 1
techs.csp.costs.spores_score.energy_cap: 0
techs.csp.costs.spores_score.interest_rate: 1
techs.battery.costs.spores_score.energy_cap: 0
techs.battery.costs.spores_score.interest_rate: 1
techs.ac_transmission.costs.spores_score.energy_cap: 0
techs.ac_transmission.costs.spores_score.interest_rate: 1
```

Note: We use and recommend using 'spores_score' and 'systemwide_cost_max' to define the cost class and group constraint, respectively. However, these are user-defined, allowing you to choose terminology that best fits your use-case.

1.8.7 Generating scripts to run a model many times

Scenarios and overrides can be used to run a given model multiple times with slightly changed settings or constraints.

This functionality can be used together with the `calliope generate_runs` and `calliope generate_scenarios` command-line tools to generate scripts that run a model many times over in a fully automated way, for example, to explore the effect of different technology costs on model results.

`calliope generate_runs`, at a minimum, must be given the following arguments:

- the model configuration file to use
- the name of the script to create
- `--kind`: Currently, three options are available. `windows` creates a Windows batch (`.bat`) script that runs all models sequentially, `bash` creates an equivalent script to run on Linux or macOS, `bsub` creates a submission script for a LSF-based high-performance cluster, and `sbatch` creates a submission script for a SLURM-based high-performance cluster.
- `--scenarios`: A semicolon-separated list of scenarios (or overrides/combinations of overrides) to generate scripts for, for example, `scenario1;scenario2` or `override1,override2a;override1,override2b`. Note that when not using manually defined scenario names, a comma is used to group overrides together into a single model – in the above example, `override1,override2a` would be applied to the first run and `override1,override2b` be applied to the second run

A fully-formed command generating a Windows batch script to run a model four times with each of the scenarios "run1", "run2", "run3", and "run4":

```
calliope generate_runs model.yaml run_model.bat --kind=windows --scenarios "run1;run2;
↪run3;run4"
```

Optional arguments are:

- `--cluster_threads`: specifies the number of threads to request on a HPC cluster
- `--cluster_mem`: specifies the memory to request on a HPC cluster
- `--cluster_time`: specifies the run time to request on a HPC cluster
- `--additional_args`: A text string of any additional arguments to pass directly through to `calliope run` in the generated scripts, for example, `--additional_args="-debug"`.
- `--debug`: Print additional debug information when running the run generation script.

An example generating a script to run on a bsub-type high-performance cluster, with additional arguments to specify the resources to request from the cluster:

```
calliope generate_runs model.yaml submit_runs.sh --kind=bsub --cluster_mem=1G --cluster_
↪time=100 --cluster_threads=5  --scenarios "run1;run2;run3;run4"
```

Running this will create two files:

- `submit_runs.sh`: The cluster submission script to pass to `bsub` on the cluster.
- `submit_runs.array.sh`: The accompanying script defining the runs for the cluster to execute.

In all cases, results are saved into the same directory as the script, with filenames of the form `out_{run_number}_{scenario_name}.nc` (model results) and `plots_{run_number}_{scenario_name}.html` (HTML plots), where `{run_number}` is the run number and `{scenario_name}` is the name of the scenario (or the string defining the overrides applied). On a cluster, log files are saved to files with names starting with `log_` in the same directory.

Finally, the `calliope generate_scenarios` tool can be used to quickly generate a file with `scenarios` definition for inclusion in a model, if a large enough number of overrides exist to make it tedious to manually combine them into scenarios. Assuming that in `model.yaml` a range of overrides exist that specify a subset of time for the years 2000 through 2010, called "y2000" through "y2010", and a set of cost-related overrides called "cost_low", "cost_medium" and "cost_high", the following command would generate scenarios with combinations of all years and cost overrides, calling them "run_1", "run_2", and so on, and saving them to `scenarios.yaml`:

```
calliope generate_scenarios model.yaml scenarios.yaml y2000;y2001;y2002;2003;y2004;y2005;
↪y2006;2007;2008;y2009;2010 cost_low;cost_medium;cost_high --scenario_name_prefix="run_"
```

1.8.8 Importing other YAML files in overrides

When using overrides (see *Scenarios and overrides*), it is possible to have `import` statements within overrides for more flexibility. The following example illustrates this:

```
overrides:
    some_override:
        techs:
            some_tech.constraints.energy_cap_max: 10
        import: [additional_definitions.yaml]
```

additional_definitions.yaml:

```
techs:
    some_other_tech.constraints.energy_eff: 0.1
```

This is equivalent to the following override:

```
overrides:
    some_override:
        techs:
            some_tech.constraints.energy_cap_max: 10
            some_other_tech.constraints.energy_eff: 0.1
```

1.8.9 Interfacing with the solver backend

On loading a model, there is no solver backend, only the input dataset. The backend is generated when a user calls *run()* on their model. Currently this will call back to Pyomo to build the model and send it off to the solver, given by the user in the run configuration `run.solver`. Once built, solved, and returned, the user has access to the results dataset `model.results` and interface functions with the backend `model.backend`.

You can use this interface to:

1. **Get the raw data on the inputs used in the optimisation.** By running `model.backend.get_input_params()` a user get an xarray Dataset which will look very similar to `model.inputs`, except that assumed default values will be included. You may also spot a bug, where a value in `model.inputs` is different to the value returned by this function.
2. **Update a parameter value.** If you are interested in updating a few values in the model, you can run `model.backend.update_param()`. For example, to update the energy efficiency of your *ccgt* technology in location *region1* from 0.5 to 0.1, you can run `model.backend.update_param('energy_eff', {'region1::ccgt: 0.1})`. This will not affect results at this stage, you'll need to rerun the backend (point 4) to optimise with these new values.

Note: If you are interested in updating the objective function cost class weights, you will need to set 'objective_cost_class' as the parameter, e.g. `model.backend.update_param('objective_cost_class', {'monetary': 0.5})`.

---

3. **Activate / Deactivate a constraint or objective.** Constraints can be activated and deactivate such that they will or will not have an impact on the optimisation. All constraints are active by default, but you might like to remove, for example, a capacity constraint if you don't want there to be a capacity limit for any technologies. Similarly, if you had multiple objectives, you could deactivate one and activate another. The result would be to have a different objective when rerunning the backend.

Note: Currently Calliope does not allow you to build multiple objectives, you will need to understand Pyomo and add an additional objective yourself to make use of this functionality. The Pyomo ConcreteModel() object can be accessed at `model._backend_model`.

---

4. **Rerunning the backend.** If you have edited parameters or constraint activation, you will need to rerun the optimisation to propagate the effects. By calling `model.backend.rerun()`, the optimisation will run again, with the updated backend. This will not affect your model, but instead will return a new calliope Model object associated with that *specific* rerun. You can analyse the results and inputs in this new model, but there is no backend interface available. You'll need to return to the original model to access the backend again, or run the returned model using `new_model.run(force_rerun=True)`. In the original model, `model.results` will not change, and can only be overwritten by `model.run(force_rerun=True)`.

Note: By calling `model.run(force_rerun=True)` any updates you have made to the backend will be overwritten.

See also:

Pyomo backend interface

1.8.10 Specifying custom solver options

Gurobi

Refer to the Gurobi manual, which contains a list of parameters. Simply use the names given in the documentation (e.g. "NumericFocus" to set the numerical focus value). For example:

```
run:
    solver: gurobi
    solver_options:
        Threads: 3
        NumericFocus: 2
```

CPLEX

Refer to the CPLEX parameter list. Use the "Interactive" parameter names, replacing any spaces with underscores (for example, the memory reduction switch is called "emphasis memory", and thus becomes "emphasis_memory"). For example:

```
run:
    solver: cplex
    solver_options:
        mipgap: 0.01
        mip_polishafter_absmipgap: 0.1
        emphasis_mip: 1
        mip_cuts: 2
        mip_cuts_cliques: 3
```

1.9 Configuration and defaults

This section lists the available configuration options and constraints along with their default values. Defaults are automatically applied in constraints whenever there is no user input for a particular value.

1.9.1 Model configuration

Setting	Default	Comments
calliope_version		Calliope framework version this model is intended for
group_share	{}	Optional settings for the group_share constraint - deprecated and will be removed in v0.7.0
name		Model name
random_seed		Seed for random number generator used during clustering
reserve_margin	{}	Per-carrier system-wide reserve margins
subset_time		Subset of timesteps as a two-element list giving the range, e.g. ['2005-01-01', '2005-01-05'], or a single string, e.g. '2005-01'
time	{}	Optional settings to adjust time resolution, see *Time resolution adjustment* for the available options
timeseries_data_path		Path to time series data
timeseries_data		Dict of dataframes with time series data (when passing in dicts rather than YAML files to Model constructor)
timeseries_dateformat	%Y-%m-%d %H:%M:%S	Timestamp format of all time series data when read from file
file_allowed	['clustering_func', 'energy_con', 'energy_eff', 'energy_prod', 'energy_ramping', 'export', 'force_resource', 'om_con', 'om_prod', 'parasitic_eff', 'resource', 'resource_eff', 'storage_loss', 'carrier_ratios']	List of configuration options allowed to specify "file=" to load timeseries data. This can be updated if you're adding a new custom constraint that requires a newly defined parameter to be a timeseries. If updating existing parameters, you can expect existing constraints to not change behaviour or to break on being constructed. ## # Base technology groups ##

1.9.2 Run configuration

Setting	Default	Comments
backend	pyomo	Backend to use to build and solve the model. As of v0.6.0, only *pyomo* is available
bigM	1000000000.0	Used for unmet demand, but should be of a similar order of magnitude as the largest cost that the model could achieve. Too high and the model will not converge
cyclic_storage	True	If true, storage in the last timestep of the timeseries is considered to be the 'previous timestep' in the first timestep of the timeseries
ensure_feasibility	False	If true, unmet_demand will be a decision variable, to account for an ability to meet demand with the available supply. If False and a mismatch occurs, the optimisation will fail due to infeasibility
mode	plan	Which mode to run the model in: 'plan', 'operation' or 'spores'
objective_options	{}	Arguments to pass to objective function. If cost-based objective function in use, should include 'cost_class' and 'sense' (maximize/minimize)
objective	min-max_cost_optimization	Name of internal objective function to use, currently only min/max cost-based optimisation is available
operation	{}	Settings for operational mode
spores_options	{}	settings for SPORES (spatially-explicit, practically optimal results) mode
relax_constraint	{}	Enable relaxing some equality constraints to be min/max constraints. The extent of relaxation is given as a fraction.
save_logs		Directory into which to save logs and temporary files. Also turns on symbolic solver labels in the Pyomo backend
solver_io		What method the Pyomo backend should use to communicate with the solver
solver_options		A list of options, which are passed on to the chosen solver, and are therefore solver-dependent
solver	cbc	Which solver to use
zero_threshold	1e-10	Any value coming out of the backend that is smaller than this threshold (due to floating point errors, probably) will be set to zero

1.9.3 Per-tech constraints

The following table lists all available technology constraint settings and their default values. All of these can be set by `tech_identifier.constraints.constraint_name`, e.g. `nuclear.constraints.energy_cap.max`.

Setting	Default	Name	Unit	Comments
carrier_ratios		Carrier ratios	fraction	Ratio of summed output of carriers in ['out_2', 'out_3'] / ['in_2', 'in_3'] to the summed output of carriers in 'out' / 'in'. given in a nested dictionary.
charge_rate		Charge rate	hour $^{-1}$	(do not use, replaced by energy_cap_per_storage_cap_max) ratio of maximum charge/discharge (kW) for a given maximum storage capacity (kWh).
energy_cap_per_storage_cap_min	0	Minimum energy capacity per storage capacity	hour $^{-1}$	ratio of minimum charge/discharge (kW) for a given storage capacity (kWh).
energy_cap_per_storage_cap_max	inf	Maximum energy capacity per storage capacity	hour $^{-1}$	ratio of maximum charge/discharge (kW) for a given storage capacity (kWh).
energy_cap_per_storage_cap_equals		Tie energy capacity to storage capacity	hour $^{-1}$	
energy_cap_equals		Specific installed energy capacity	kW	fixes maximum/minimum if decision variables `carrier_prod`/`carrier_con` and overrides `_max` and `_min` constraints.
energy_cap_equals_systemwide		System-wide specific installed energy capacity	kW	fixes the sum to a maximum/minimum, for a particular technology, of the decision variables `carrier_prod`/`carrier_con` over all locations.
energy_cap_max	inf	Maximum installed energy capacity	kW	Limits decision variables `carrier_prod`/`carrier_con` to a maximum/minimum.
energy_cap_max_systemwide	inf	System-wide maximum installed energy capacity	kW	Limits the sum to a maximum/minimum, for a particular technology, of the decision variables `carrier_prod`/`carrier_con` over all locations.
energy_cap_min	0	Minimum installed energy capacity	kW	Limits decision variables `carrier_prod`/`carrier_con` to a minimum/maximum.
energy_cap_min_use	0	Minimum carrier production	fraction	Set to a value between 0 and 1 to force minimum carrier production as a fraction of the technology maximum energy capacity. If non-zero and technology is not defined by `units`, this will force the technology to operate above its minimum value at every timestep.
energy_cap_per_unit		Energy capacity per purchased unit	kW/unit	Set the capacity of each integer unit of a technology purchased

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Table 2 – continued from previous page

Setting	Default	Name	Unit	Comments
energy_cap_scale	1.0	Energy capacity scale	float	Scale all `energy_cap` min/max/equals/total_max/total_equals constraints by this value
energy_con	False	Energy consumption	boolean	Allow this technology to consume energy from the carrier (static boolean, or from file as timeseries).
energy_eff	1.0	Energy efficiency	fraction	conversion efficiency (static, or from file as timeseries), from `resource/storage/carrier_in` (tech dependent) to `carrier_out`.
energy_eff_per_distance	1.0	Energy efficiency per distance	fraction/distance	Set as value between 1 (no loss) and 0 (all energy lost).
energy_prod	False	Energy production	boolean	Allow this technology to supply energy to the carrier (static boolean, or from file as timeseries).
energy_ramping		Ramping rate	fraction / hour	Set to `null` to disable ramping constraints, otherwise limit maximum carrier production to a fraction of maximum capacity, which increases by that fraction at each timestep.
export_cap	inf	Export capacity	kW	Maximum allowed export of produced energy carrier for a technology.
export_carrier		Export carrier	N/A	Name of carrier to be exported. Must be an output carrier of the technology
force_asynchronous_prod_con	False	Force asynchronous production consumption	boolean	If True, carrier_prod and carrier_con cannot both occur in the same timestep
force_resource	False	Force resource	boolean	Forces this technology to use all available `resource`, rather than making it a maximum upper boundary (for production) or minimum lower boundary (for consumption). Static boolean, or from file as timeseries
lifetime		Technology lifetime	years	Must be defined if fixed capital costs are defined. A reasonable value for many technologies is around 20-25 years.
one_way	False	One way	boolean	Forces a transmission technology to only move energy in one direction on the link, in this case from *default_location_from* to *default_location_to*
parasitic_eff	1.0	Plant parasitic efficiency	fraction	Additional losses as energy gets transferred from the plant to the carrier (static, or from file as timeseries), e.g. due to plant parasitic consumption

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Setting	Default	Name	Unit	Comments
resource	0	Available resource	kWh | kWh/m^2 | kWh/kW	Maximum available resource (static, or from file as timeseries). Unit dictated by `resource_unit`
resource_area_equals		Specific installed resource area	m^2	
resource_area_max	inf	Maximum usable resource area	m^2	If set to a finite value, restricts the usable area of the technology to this value.
resource_area_min	0	Minimum usable resource area	m^2	
resource_area_per_energy_cap		Resource area per energy capacity	m:sup:*2*/kW	If set, forces `resource_area` to follow `energy_cap` with the given numerical ratio (e.g. setting to 1.5 means that `resource_area == 1.5 * energy_cap`)
resource_cap_equals		Specific installed resource consumption capacity	kW	overrides `_max` and `_min` constraints.
resource_cap_equals_energy_cap	False	Resource capacity equals energy cpacity	boolean	If true, `resource_cap` is forced to equal `energy_cap`
resource_cap_max	inf	Maximum installed resource consumption capacity	kW	
resource_cap_min	0	Minimum installed resource consumption capacity	kW	
resource_eff	1.0	Resource efficiency	fraction	Efficiency (static, or from file as timeseries) in capturing resource before it reaches storage (if storage is present) or conversion to carrier.
resource_min_use	0	Minimum resource consumption	fraction	Set to a value between 0 and 1 to force minimum resource consumption for production technologies
resource_scale	1.0	Resource scale	fraction	Scale resource (either static value or all values in timeseries) by this value
resource_unit	energy	Resource unit	N/A	Sets the unit of `resource` to either `energy` (i.e. kWh), `energy_per_area` (i.e. kWh/m2), or `energy_per_cap` (i.e. kWh/kW). `energy_per_area` uses the `resource_area` decision variable to scale the available resource while `energy_per_cap` uses the `energy_cap` decision variable.

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Setting	Default	Name	Unit	Comments
storage_cap_equals		Specific storage capacity	kWh	If not defined, `energy_cap_equals * energy_cap_per_storage_cap_max` will be used as the capacity and overrides `_max` and `_min` constraints.
storage_cap_max	inf	Maximum storage capacity	kWh	If not defined, `energy_cap_max * energy_cap_per_storage_cap_max` will be used as the capacity.
storage_cap_min	0	Minimum storage capacity	kWh	
storage_cap_per_unit		Storage capacity per purchased unit	kWh/unit	Set the storage capacity of each integer unit of a technology purchased.
storage_discharge_depth	0	Storage depth of discharge	fraction	Defines the minimum level of storage state of charge, as a fraction of total storage capacity
storage_initial	0	Initial storage level	fraction	Set stored energy in device at the first timestep, as a fraction of total storage capacity
storage_loss	0	Storage loss rate	fraction/hour	rate of storage loss per hour (static, or from file as timeseries), used to calculate lost stored energy as `(1 - storage_loss)^hours_per_timestep`
units_equals		Specific number of purchased units	integer	Turns the model from LP to MILP.
units_equals_systemwide		System-wide specific installed energy capacity	kW	fixes the sum to a specific value, for a particular technology, of the decision variables `carrier_prod`/`carrier_con` over all locations.
units_max		Maximum number of purchased units	integer	Turns the model from LP to MILP.
units_max_systemwide	inf	System-wide maximum installed energy capacity	kW	Limits the sum to a maximum/minimum, for a particular technology, of the decision variables `carrier_prod`/`carrier_con` over all locations.
units_min		Minimum number of purchased units	integer	Turns the model from LP to MILP.

1.9.4 Per-tech costs

These are all the available costs, which are set to 0 by default for every defined cost class. Costs are set by `tech_identifier.costs.cost_class.cost_name`, e.g. `nuclear.costs.monetary.energy_cap`.

Setting	Default	Name	Unit	Comments
energy_cap	0	Cost of energy capacity	kW_{gross}^{-1}	
energy_cap_per_distance	0	Cost of energy capacity, per unit distance	kW_{gross}^{-1} / distance	Applied to transmission links only
export	0	Carrier export cost	kWh^{-1}	Usually used in the negative sense, as a subsidy.
interest_rate	0	Interest rate	fraction	Used when computing levelized costs
om_annual	0	Yearly O&M costs	$kW_{energy\_cap}^{-1}$	
om_annual_investment_fraction	0	Fractional yearly O&M costs	fraction / total investment	
om_con	0	Carrier consumption cost	kWh^{-1}	Applied to carrier consumption of a technology
om_prod	0	Carrier production cost	kWh^{-1}	Applied to carrier production of a technology
purchase	0	Purchase cost	$unit^{-1}$	Triggers a binary variable for that technology to say that it has been purchased or is applied to integer variable `units`
resource_area	0	Cost of resource area	m^{-2}	
resource_cap	0	Cost of resource consumption capacity	kW^{-1}	
storage_cap	0	Cost of storage capacity	kWh^{-1}	

Technology depreciation settings apply when calculating levelized costs. The interest rate and life times must be set for each technology with investment costs.

1.9.5 Group constraints

See *Group constraints* for a full listing of available group constraints.

1.9.6 Abstract base technology groups

Technologies must always define a parent, and this can either be one of the pre-defined abstract base technology groups or a user-defined group (see *Using tech_groups to group configuration*). The pre-defined groups are:

- `supply`: Supplies energy to a carrier, has a positive resource.
- `supply_plus`: Supplies energy to a carrier, has a positive resource. Additional possible constraints, including efficiencies and storage, distinguish this from `supply`.
- `demand`: Demands energy from a carrier, has a negative resource.

- `storage`: Stores energy.
- `transmission`: Transmits energy from one location to another.
- `conversion`: Converts energy from one carrier to another.
- `conversion_plus`: Converts energy from one or more carrier(s) to one or more different carrier(s).

A technology inherits the configuration that its parent group specifies (which, in turn, may inherit from its own parent).

Note: The identifiers of the abstract base tech groups are reserved and cannot be used for user-defined technologies. However, you can amend an abstract base technology group for example by a lifetime attribute that will be in effect for all technologies derived from that group (see *Using tech_groups to group configuration*).

The following lists the pre-defined base tech groups and the defaults they provide.

supply

Default constraints provided by the parent tech group:

```
essentials:
  parent:
constraints:
  energy_prod: true
  resource: inf
  resource_unit: energy
costs: {}
```

Required constraints, allowed constraints, and allowed costs:

```
required_constraints: []
allowed_constraints:
-   energy_cap_equals
-   energy_cap_equals_systemwide
-   energy_cap_max
-   energy_cap_max_systemwide
-   energy_cap_min
-   energy_cap_min_use
-   energy_cap_per_unit
-   energy_cap_scale
-   energy_eff
-   energy_prod
-   energy_ramping
-   export_cap
-   export_carrier
-   force_resource
-   lifetime
-   resource
-   resource_area_equals
-   resource_area_max
-   resource_area_min
-   resource_area_per_energy_cap
```

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```
-   resource_min_use
-   resource_scale
-   resource_unit
-   units_equals
-   units_equals_systemwide
-   units_max
-   units_max_systemwide
-   units_min
allowed_costs:
-   depreciation_rate
-   energy_cap
-   export
-   interest_rate
-   om_annual
-   om_annual_investment_fraction
-   om_con
-   om_prod
-   purchase
-   resource_area
```

supply_plus

Default constraints provided by the parent tech group:

```
essentials:
  parent:
constraints:
  energy_prod: true
  resource: inf
  resource_eff: 1.0
  resource_unit: energy
costs: {}
```

Required constraints, allowed constraints, and allowed costs:

```
required_constraints: []
allowed_constraints:
-   charge_rate
-   energy_cap_per_storage_cap_min
-   energy_cap_per_storage_cap_max
-   energy_cap_per_storage_cap_equals
-   energy_cap_equals
-   energy_cap_equals_systemwide
-   energy_cap_max
-   energy_cap_max_systemwide
-   energy_cap_min
-   energy_cap_min_use
-   energy_cap_per_unit
-   energy_cap_scale
-   energy_eff
```

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```
-   energy_prod
-   energy_ramping
-   export_cap
-   export_carrier
-   force_resource
-   lifetime
-   parasitic_eff
-   resource
-   resource_area_equals
-   resource_area_max
-   resource_area_min
-   resource_area_per_energy_cap
-   resource_cap_equals
-   resource_cap_equals_energy_cap
-   resource_cap_max
-   resource_cap_min
-   resource_eff
-   resource_min_use
-   resource_scale
-   resource_unit
-   storage_cap_equals
-   storage_cap_max
-   storage_cap_min
-   storage_cap_per_unit
-   storage_initial
-   storage_loss
-   units_equals
-   units_equals_systemwide
-   units_max
-   units_max_systemwide
-   units_min
allowed_costs:
-   depreciation_rate
-   energy_cap
-   export
-   interest_rate
-   om_annual
-   om_annual_investment_fraction
-   om_con
-   om_prod
-   purchase
-   resource_area
-   resource_cap
-   storage_cap
```

demand

Default constraints provided by the parent tech group:

```
essentials:
  parent:
constraints:
  energy_con: true
  force_resource: true
  resource_unit: energy
costs: {}
```

Required constraints, allowed constraints, and allowed costs:

```
required_constraints:
-   resource
allowed_constraints:
-   energy_con
-   force_resource
-   resource
-   resource_area_equals
-   resource_scale
-   resource_unit
allowed_costs:
-   om_con
```

storage

Default constraints provided by the parent tech group:

```
essentials:
  parent:
constraints:
  energy_con: true
  energy_prod: true
  storage_cap_max: inf
costs: {}
```

Required constraints, allowed constraints, and allowed costs:

```
required_constraints: []
allowed_constraints:
-   charge_rate
-   energy_cap_per_storage_cap_min
-   energy_cap_per_storage_cap_max
-   energy_cap_per_storage_cap_equals
-   energy_cap_equals
-   energy_cap_equals_systemwide
-   energy_cap_max
-   energy_cap_max_systemwide
```

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```
-   energy_cap_min
-   energy_cap_min_use
-   energy_cap_per_unit
-   energy_cap_scale
-   energy_con
-   energy_eff
-   energy_prod
-   energy_ramping
-   export_cap
-   export_carrier
-   force_asynchronous_prod_con
-   lifetime
-   storage_cap_equals
-   storage_cap_max
-   storage_cap_min
-   storage_cap_per_unit
-   storage_initial
-   storage_loss
-   storage_time_max
-   storage_discharge_depth
-   units_equals
-   units_equals_systemwide
-   units_max
-   units_max_systemwide
-   units_min
allowed_costs:
-   depreciation_rate
-   energy_cap
-   export
-   interest_rate
-   om_annual
-   om_annual_investment_fraction
-   om_prod
-   purchase
-   storage_cap
```

transmission

Default constraints provided by the parent tech group:

```
essentials:
  parent:
constraints:
  energy_con: true
  energy_prod: true
costs: {}
```

Required constraints, allowed constraints, and allowed costs:

```
required_constraints: []
allowed_constraints:
-   energy_cap_equals
-   energy_cap_min
-   energy_cap_max
-   energy_cap_per_unit
-   energy_cap_scale
-   energy_con
-   energy_eff
-   energy_eff_per_distance
-   energy_prod
-   force_asynchronous_prod_con
-   lifetime
-   one_way
allowed_costs:
-   depreciation_rate
-   energy_cap
-   energy_cap_per_distance
-   interest_rate
-   om_annual
-   om_annual_investment_fraction
-   om_prod
-   purchase
-   purchase_per_distance
```

conversion

Default constraints provided by the parent tech group:

```
essentials:
  parent:
constraints:
  energy_con: true
  energy_prod: true
costs: {}
```

Required constraints, allowed constraints, and allowed costs:

```
required_constraints: []
allowed_constraints:
-   energy_cap_equals
-   energy_cap_equals_systemwide
-   energy_cap_max
-   energy_cap_max_systemwide
-   energy_cap_min
-   energy_cap_min_use
-   energy_cap_per_unit
-   energy_cap_scale
-   energy_con
-   energy_eff
```

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```
-   energy_prod
-   energy_ramping
-   export_cap
-   export_carrier
-   lifetime
-   units_equals
-   units_equals_systemwide
-   units_max
-   units_max_systemwide
-   units_min
allowed_costs:
-   depreciation_rate
-   energy_cap
-   export
-   interest_rate
-   om_annual
-   om_annual_investment_fraction
-   om_con
-   om_prod
-   purchase
```

conversion_plus

Default constraints provided by the parent tech group:

```
essentials:
  parent:
constraints:
  energy_con: true
  energy_prod: true
costs: {}
```

Required constraints, allowed constraints, and allowed costs:

```
required_constraints: []
allowed_constraints:
-   carrier_ratios
-   energy_cap_equals
-   energy_cap_equals_systemwide
-   energy_cap_max
-   energy_cap_max_systemwide
-   energy_cap_min
-   energy_cap_min_use
-   energy_cap_per_unit
-   energy_cap_scale
-   energy_con
-   energy_eff
-   energy_prod
-   energy_ramping
-   export_cap
```

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```
-   export_carrier
-   lifetime
-   units_equals
-   units_equals_systemwide
-   units_max
-   units_max_systemwide
-   units_min
allowed_costs:
-   depreciation_rate
-   energy_cap
-   export
-   interest_rate
-   om_annual
-   om_annual_investment_fraction
-   om_con
-   om_prod
-   purchase
```

1.10 Troubleshooting

1.10.1 General strategies

- **Building a smaller model**: `model.subset_time` allows specifying a subset of timesteps to be used. This can be useful for debugging purposes as it can dramatically speed up model solution times. The timestep subset can be specified as `[startdate, enddate]`, e.g. `['2005-01-01', '2005-01-31']`, or as a single time period, such as `2005-01` to select January only. The subsets are processed before building the model and applying time resolution adjustments, so time resolution reduction functions will only see the reduced set of data.
- **Retaining logs and temporary files**: The setting `run.save_logs`, disabled by default, sets the directory into which to save logs and temporary files from the backend, to inspect solver logs and solver-generated model files. This also turns on symbolic solver labels in the Pyomo backend, so that all model components in the backend model are named according to the corresponding Calliope model components (by default, Pyomo uses short random names for all generated model components).
- **Analysing the optimisation problem without running the model**: If you are comfortable with navigating Pyomo objects, then you can build the Pyomo model backend without running the optimisation problem, using `model.run(build_only=True)`. Pyomo objects are then accessible within `model._backend_model`. For instance, the constraint limiting energy capacity can be viewed by calling `model._backend_model.energy_capacity_constraint.pprint('hi')`. Alternatively, if you are working from the command line or have little experience with Pyomo, you can generate an LP file. The LP file contains the mathematical model formulation of a fully built Calliope model. It is a standard format that can be passed to various solvers. Examining the LP file manually or using additional tools (see below) can help find issues when a model is infeasible or unbounded. To build a model and save it to LP without actually solving it, use:

  ```
  calliope run my_model.yaml --save_lp=my_saved_model.lp
  ```

  or, interactively:

  ```
  model.to_lp('my_saved_model.lp')
  ```

1.10.2 Improving solution times

One way to improve solution time is to reduce the size of a problem (another way is to address potential numerical issues, which is dealt with further below in *Understanding infeasibility and numerical instability*).

Number of variables

The sets `locs`, `techs`, `timesteps`, `carriers`, and `costs` all contribute to model complexity. A reduction of any of these sets will reduce the number of resulting decision variables in the optimisation, which in turn will improve solution times.

Note: By reducing the number of locations (e.g. merging nearby locations) you also remove the technologies linking those locations to the rest of the system, which is additionally beneficial.

Currently, we only provide automatic set reduction for timesteps. Timesteps can be resampled (e.g. 1hr -> 2hr intervals), masked (e.g. 1hr -> 12hr intervals except one week of particular interest), or clustered (e.g. 365 days to 5 days, each representing 73 days of the year, with 1hr resolution). In so doing, significant solution time improvements can be acheived.

See also:

Time resolution adjustment, Stefan Pfenninger (2017). Dealing with multiple decades of hourly wind and PV time series in energy models: a comparison of methods to reduce time resolution and the planning implications of inter-annual variability. Applied Energy.

Complex technologies

Calliope is primarily an LP framework, but application of certain constraints will trigger binary or integer decision variables. When triggered, a MILP model will be created.

In both cases, there will be a time penalty, as linear programming solvers are less able to converge on solutions of problems which include binary or integer decision variables. But, the additional functionality can be useful. A purchasing cost allows for a cost curve of the form $y = Mx + C$ to be applied to a technology, instead of the LP costs which are all of the form $y = Mx$. Integer units also trigger per-timestep decision variables, which allow technologies to be "on" or "off" at each timestep.

Additionally, in LP models, interactions between timesteps (in `storage` technologies) can lead to longer solution time. The exact extent of this is as-yet untested.

Model mode

Solution time increases more than linearly with the number of decision variables. As it splits the model into ~daily chunks, operational mode can help to alleviate solution time of big problems. This is clearly at the expense of fixing technology capacities. However, one solution is to use a heavily time clustered `plan` mode to get indicative model capacities. Then run `operate` mode with these capacities to get a higher resolution operation strategy. If necessary, this process could be iterated.

See also:

Operational mode

1.10.3 Influence of solver choice on speed

The open-source solvers (GLPK and CBC) are slower than the commercial solvers. If you are an academic researcher, it is recommended to acquire a free licence for Gurobi or CPLEX to very quickly improve solution times. GLPK in particular is slow when solving MILP models. CBC is an improvement, but can still be several orders of magnitude slower at reaching a solution than Gurobi or CPLEX.

We tested solution time for various solver choices on our example models, extended to run over a full year (8760 hours). These runs took place on the University of Cambridge high performance computing cluster, with a maximum run time of 5 hours. As can be seen, CBC is far superior to GLPK. If introducing binary constraints, although CBC is an improvement on GLPK, access to a commercial solver is preferable.

National scale example model size

- Variables : 420526 [Nneg: 219026, Free: 105140, Other: 96360]
- Linear constraints : 586972 [Less: 315373, Greater: 10, Equal: 271589]

MILP urban scale example model

- Variables: 586996 [Nneg: 332913, Free: 78880, Binary: 2, General Integer: 8761, Other: 166440]
- Linear constraints: 788502 [Less: 394226, Greater: 21, Equal: 394255]

Solution time

Solver	Solution time	
	National	Urban
GLPK	4:35:40	>5hrs
CBC	0:04:45	0:52:13
Gurobi (1 thread)	0:02:08	0:03:21
CPLEX (1 thread)	0:04:55	0:05:56
Gurobi (4 thread)	0:02:27	0:03:08
CPLEX (4 thread)	0:02:16	0:03:26

See also:

Specifying custom solver options

1.10.4 Understanding infeasibility and numerical instability

Note: A good first step when faced with an infeasible model is often to remove constraints, in particular more complex constraints. For example, different combinations of group constraints can easily introduce mutually exclusive requirements on capacities or output from specific technologies. Once a minimal model works, more complex constraints can be turned on again one after the other.

Using the Gurobi solver

To understand infeasible models:

- Set `run.solver_options.DualReductions: 0` to see whether a model is infeasible or unbounded.
- To analyse infeasible models, save an LP file with the `--save_lp` command-line option, then use Gurobi to generate an Irreducible Inconsistent Subsystem that shows which constraints are infeasible:

```
gurobi_cl ResultFile=result.ilp my_saved_model.lp
```

  More detail on this is in the official Gurobi documentation.

To deal with numerically unstable models, try setting `run.solver_options.Presolve: 0`, as large numeric ranges can cause the pre-solver to generate an infeasible or numerically unstable model. The Gurobi Guidelines for Numerical Issues give detailed guidance for strategies to address numerically difficult optimisation problems.

Using the CPLEX solver

There are two ways to understand infeasibility when using the CPLEX solver, the first is quick and the second is more involved:

1. Save solver logs for your model (`run.save_logs: path/to/log_directory`). In the directory, open the file ending in '.cplex.log' to see the CPLEX solver report. If the model is infeasible or unbounded, the offending constraint will be identified (e.g. "*SOLVER: Infeasible variable = slack c_u_carrier_production_max_constraint(region1_2__csp__power_2005_01_01_07_00_00)_*"). This may be enough to understand why the model is failing, if not…
2. Open the LP file in CPLEX interactive (run *cplex* in the command line to invoke a CPLEX interactive session). The LP file for the problem ends with '.lp' in the log folder (*read path/to/file.lp*). Once loaded, you can try relaxing variables / constraints to see if the problem can be solved with relaxation (*FeasOpt*). You can also identify conflicting constraints (*tools conflict*) and print those constraints directly (*display conflict all*). There are many more commands available to analyse individual constraints and variables in the Official CPLEX documentation.

Similar to Gurobi, numerically unstable models may lead to unexpected infeasibility, so you can try `run.solver_options.preprocessing_presolve: 0` or you can request CPLEX to more aggressively scale the problem itself using the solver option `read_scale: 1` . The CPLEX documentation page on numeric difficulties goes into more detail on numeric instability.

1.10.5 Rerunning a model

After running, if there is an infeasibility you want to address, or simply a few values you dont think were quite right, you can change them and rerun your model. If you change them in *model.inputs*, just rerun the model as `model.run(force_rerun=True)`.

Note: `model.run(force_rerun=True)` will replace you current model.results and rebuild he entire model backend. You may want to save your model before doing this.

Particularly if your problem is large, you may not want to rebuild the backend to change a few small values. Instead you can interface directly with the backend using the `model.backend` functions, to update individual parameter values and switch constraints on/off. By rerunning the backend specifically, you can optimise your problem with these backend changes, without rebuilding the backend entirely.

Note: `model.inputs` and `model.results` will not be changed when updating and rerunning the backend. Instead, a new xarray Dataset is returned.

See also:

Interfacing with the solver backend

1.10.6 Debugging model errors

Calliope provides a method to save its fully built and commented internal representation of a model to a single YAML file with `Model.save_commented_model_yaml(path)`. Comments in the resulting YAML file indicate where original values were overridden.

Because this is Calliope's internal representation of a model directly before the `model_data xarray.Dataset` is built, it can be useful for debugging possible issues in the model formulation, for example, undesired constraints that exist at specific locations because they were specified model-wide without having been superseded by location-specific settings.

Further processing of the data does occur before solving the model. The final values of parameters used by the backend solver to generate constraints can be analysed when running an interactive Python session by running `model.backend.get_input_params()`. This provides a user with an xarray Dataset which will look very similar to `model.inputs`, except that assumed *default values* will be included. An attempt at running the model has to be made in order to be able to run this command.

See also:

If using Calliope interactively in a Python session, we recommend reading up on the Python debugger and (if using Jupyter notebooks) making use of the %debug magic.

1.11 More info (reference)

This section contains additional information useful as reference: a list of all example models and their configuration, a listing of different possible configuration values, and the detailed mathematical formulation.

We suggest you read the *Building a model*, *Running a model* and *Analysing a model* sections first before referring to this section.

1.11.1 Built-in example models

This section gives a listing of all the YAML configuration files included in the built-in example models. Refer to the *tutorials section* for a brief overview of how these parts together provide a working model.

The example models are accessible in the `calliope.examples` module. To create an instance of an example model, call its constructor function, e.g.

```
urban_model = calliope.examples.urban_scale()
```

The available example models and their constructor functions are:

`calliope.examples.`**`national_scale`**`(`*args*, ***kwargs*`)`
Returns the built-in national-scale example model.

`calliope.examples.`**`time_clustering`**`(`*args*, ***kwargs*`)`
Returns the built-in national-scale example model with time clustering.

calliope.examples.**time_resampling**(**args*, ***kwargs*)
Returns the built-in national-scale example model with time resampling.

calliope.examples.**urban_scale**(**args*, ***kwargs*)
Returns the built-in urban-scale example model.

calliope.examples.**milp**(**args*, ***kwargs*)
Returns the built-in urban-scale example model with MILP constraints enabled.

calliope.examples.**operate**(**args*, ***kwargs*)
Returns the built-in urban-scale example model in operate mode.

calliope.examples.**time_masking**(**args*, ***kwargs*)
Returns the built-in urban-scale example model with time masking.

National-scale example

Available as *calliope.examples.national_scale*.

Model settings

The layout of the model directory is as follows (+ denotes directories, - files):

```
- model.yaml
- scenarios.yaml
+ timeseries_data
    - csp_resource.csv
    - demand-1.csv
    - demand-2.csv
+ model_config
    - locations.yaml
    - techs.yaml
```

model.yaml:

```yaml
import:  # Import other files from paths relative to this file, or absolute paths
    - 'model_config/techs.yaml'  # This file specifies the model's technologies
    - 'model_config/locations.yaml'  # This file specifies the model's locations
    - 'scenarios.yaml'  # Scenario and override group definitions

# Model configuration: all settings that affect the built model
model:
    name: National-scale example model

    # What version of Calliope this model is intended for
    calliope_version: 0.6.8

    # Time series data path - can either be a path relative to this file, or an absolute␣
↪path
    timeseries_data_path: 'timeseries_data'

    subset_time: ['2005-01-01', '2005-01-05']  # Subset of timesteps

# Run configuration: all settings that affect how the built model is run
```

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```
run:
    solver: cbc

    ensure_feasibility: true  # Switches on the "unmet demand" constraint

    bigM: 1e6  # Sets the scale of unmet demand, which cannot be too high, otherwise the␣
↪optimisation will not converge

    zero_threshold: 1e-10  # Any value coming out of the backend that is smaller than␣
↪this (due to floating point errors, probably) will be set to zero

    mode: plan  # Choices: plan, operate

    objective_options.cost_class: {monetary: 1}
```

scenarios.yaml:

```
##
# Scenarios are optional, named combinations of overrides
##
scenarios:
    cold_fusion_with_production_share: ['cold_fusion', 'cold_fusion_prod_share']
    cold_fusion_with_capacity_share: ['cold_fusion', 'cold_fusion_cap_share']


##
# Overrides are the building blocks from which scenarios can be defined
##
overrides:
    profiling:
        model.name: 'National-scale example model (profiling run)'
        model.subset_time: ['2005-01-01', '2005-01-15']
        run.solver: cbc

    time_resampling:
        model.name: 'National-scale example model with time resampling'
        model.subset_time: '2005-01'
        # Resample time resolution to 6-hourly
        model.time: {function: resample, function_options: {'resolution': '6H'}}

    time_clustering:
        model.random_seed: 23
        model.name: 'National-scale example model with time clustering'
        model.subset_time: null  # No time subsetting
        # Cluster timesteps using k-means
        model.time: {function: apply_clustering, function_options: {clustering_func:
↪'kmeans', how: 'closest', k: 10}}

    spores:
        run.mode: spores
        run.spores_options:
            score_cost_class: 'spores_score'
```

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```
            slack_cost_group: 'systemwide_cost_max'
            slack: 0.1
            spores_number: 3
            objective_cost_class: {'monetary': 0, 'spores_score': 1}
        run.objective_options.cost_class: {'monetary': 1, 'spores_score': 0}
        group_constraints:
            systemwide_cost_max.cost_max.monetary: 1e10  # very large, non-infinite value

        techs.ccgt.costs.spores_score.energy_cap: 0
        techs.ccgt.costs.spores_score.interest_rate: 1
        techs.csp.costs.spores_score.energy_cap: 0
        techs.csp.costs.spores_score.interest_rate: 1
        techs.battery.costs.spores_score.energy_cap: 0
        techs.battery.costs.spores_score.interest_rate: 1
        techs.ac_transmission.costs.spores_score.energy_cap: 0
        techs.ac_transmission.costs.spores_score.interest_rate: 1

    operate:
        run.mode: operate
        run.operation:
            window: 12
            horizon: 24
        model.subset_time: ['2005-01-01', '2005-01-10']
        locations:
            region1.techs.ccgt.constraints.energy_cap_equals: 30000

            region2.techs.battery.constraints.energy_cap_equals: 1000
            region2.techs.battery.constraints.storage_cap_equals: 5240

            region1-1.techs.csp.constraints.energy_cap_equals: 10000
            region1-1.techs.csp.constraints.storage_cap_equals: 244301
            region1-1.techs.csp.constraints.resource_area_equals: 130385

            region1-2.techs.csp.constraints.energy_cap_equals: 0
            region1-2.techs.csp.constraints.storage_cap_equals: 0
            region1-2.techs.csp.constraints.resource_area_equals: 0

            region1-3.techs.csp.constraints.energy_cap_equals: 2534
            region1-3.techs.csp.constraints.storage_cap_equals: 25301
            region1-3.techs.csp.constraints.resource_area_equals: 8487

        links:
            region1,region2.techs.ac_transmission.constraints.energy_cap_equals: 3231
            region1,region1-1.techs.free_transmission.constraints.energy_cap_equals: 9000
            region1,region1-2.techs.free_transmission.constraints.energy_cap_equals: 0
            region1,region1-3.techs.free_transmission.constraints.energy_cap_equals: 2281

    check_feasibility:
        run:
            ensure_feasibility: False
            objective: 'check_feasibility'
        model:
```

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```
            subset_time: '2005-01-04'

    reserve_margin:
        model:
            # Model-wide settings for the system-wide reserve margin
            # Even setting a reserve margin of zero activates the constraint,
            # forcing enough installed capacity to cover demand in
            # the maximum demand timestep
            reserve_margin:
                power: 0.10  # 10% reserve margin for power

    ##
    # Overrides to demonstrate the run generator ("calliope generate_runs")
    ##

    run1:
        model.subset_time: ['2005-01-01', '2005-01-31']
    run2:
        model.subset_time: ['2005-02-01', '2005-02-31']
    run3:
        model.subset_time: ['2005-01-01', '2005-01-31']
        locations.region1.techs.ccgt.constraints.energy_cap_max: 0  # Disallow CCGT
    run4:
        subset_time: ['2005-02-01', '2005-02-31']
        locations.region1.techs.ccgt.constraints.energy_cap_max: 0  # Disallow CCGT

    ##
    # Overrides to demonstrate group constraints
    ##

    cold_fusion:  # Defines a hypothetical cold fusion tech to use in group constraints
        techs:
            cold_fusion:
                essentials:
                    name: 'Cold fusion'
                    color: '#233B39'
                    parent: supply
                    carrier_out: power
                constraints:
                    energy_cap_max: 10000
                    lifetime: 50
                costs:
                    monetary:
                        interest_rate: 0.20
                        energy_cap: 100
        locations.region1.techs.cold_fusion: null
        locations.region2.techs.cold_fusion: null

    cold_fusion_prod_share:
        group_constraints:
            min_carrier_prod_share_group:
                techs: ['csp', 'cold_fusion']
```

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```
                carrier_prod_share_min:
                    # At least 85% of power supply must come from CSP and cold fusion␣
↪together
                    power: 0.85

    cold_fusion_cap_share:
        group_constraints:
            max_cap_share_group:
                techs: ['csp', 'cold_fusion']
                # At most 20% of total energy_cap can come from CSP and cold fusion␣
↪together
                energy_cap_share_max: 0.20
        locations:
            region1:
                techs:
                    ccgt:
                        constraints:
                            energy_cap_max: 100000  # Increased to keep model feasible

    minimize_emissions_costs:
        run:
            objective_options:
                cost_class: {'emissions': 1, 'monetary': 0}
        techs:
            ccgt:
                costs:
                    emissions:
                        om_prod: 100 # kgCO2/kWh
            csp:
                costs:
                    emissions:
                        om_prod: 10 # kgCO2/kWh

    maximize_utility_costs:
        run:
            objective_options:
                cost_class: {'utility': 1 , 'monetary': 0}
                sense: maximize
        techs:
            ccgt:
                costs:
                    utility:
                        om_prod: 10 # arbitrary utility value
            csp:
                costs:
                    utility:
                        om_prod: 100 # arbitrary utility value

    capacity_factor:
        techs.ccgt.constraints.capacity_factor_min: 0.8
        techs.ccgt.constraints.capacity_factor_max: 0.9
```

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```
    eurocalliope:
        techs.battery.constraints.link_con_to_prod: [ccgt]
        locations.region2.techs.ccgt.constraints.energy_cap_max: 1000
```

techs.yaml:

```
##
# TECHNOLOGY DEFINITIONS
##

# Note: '-start' and '-end' is used in tutorial documentation only

techs:

    ##
    # Supply
    ##

    # ccgt-start
    ccgt:
        essentials:
            name: 'Combined cycle gas turbine'
            color: '#E37A72'
            parent: supply
            carrier_out: power
        constraints:
            resource: inf
            energy_eff: 0.5
            energy_cap_max: 40000  # kW
            energy_cap_max_systemwide: 100000  # kW
            energy_ramping: 0.8
            lifetime: 25
        costs:
            monetary:
                interest_rate: 0.10
                energy_cap: 750  # USD per kW
                om_con: 0.02  # USD per kWh
    # ccgt-end

    # csp-start
    csp:
        essentials:
            name: 'Concentrating solar power'
            color: '#F9CF22'
            parent: supply_plus
            carrier_out: power
        constraints:
            storage_cap_max: 614033
            energy_cap_per_storage_cap_max: 1
            storage_loss: 0.002
            resource: file=csp_resource.csv
            resource_unit: energy_per_area
```

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```
            energy_eff: 0.4
            parasitic_eff: 0.9
            resource_area_max: inf
            energy_cap_max: 10000
            lifetime: 25
        costs:
            monetary:
                interest_rate: 0.10
                storage_cap: 50
                resource_area: 200
                resource_cap: 200
                energy_cap: 1000
                om_prod: 0.002
    # csp-end

    ##
    # Storage
    ##
    # battery-start
    battery:
        essentials:
            name: 'Battery storage'
            color: '#3B61E3'
            parent: storage
            carrier: power
        constraints:
            energy_cap_max: 1000  # kW
            storage_cap_max: inf
            energy_cap_per_storage_cap_max: 4
            energy_eff: 0.95  # 0.95 * 0.95 = 0.9025 round trip efficiency
            storage_loss: 0  # No loss over time assumed
            lifetime: 25
        costs:
            monetary:
                interest_rate: 0.10
                storage_cap: 200  # USD per kWh storage capacity
    # battery-end

    ##
    # Demand
    ##
    # demand-start
    demand_power:
        essentials:
            name: 'Power demand'
            color: '#072486'
            parent: demand
            carrier: power
    # demand-end

    ##
    # Transmission
```

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```
    ##

    # transmission-start
    ac_transmission:
        essentials:
            name: 'AC power transmission'
            color: '#8465A9'
            parent: transmission
            carrier: power
        constraints:
            energy_eff: 0.85
            lifetime: 25
        costs:
            monetary:
                interest_rate: 0.10
                energy_cap: 200
                om_prod: 0.002

    free_transmission:
        essentials:
            name: 'Local power transmission'
            color: '#6783E3'
            parent: transmission
            carrier: power
        constraints:
            energy_cap_max: inf
            energy_eff: 1.0
        costs:
            monetary:
                om_prod: 0
    # transmission-end
```

locations.yaml:

```
##
# LOCATIONS
##

locations:
    # region-1-start
    region1:
        coordinates: {lat: 40, lon: -2}
        techs:
            demand_power:
                constraints:
                    resource: file=demand-1.csv:demand
            ccgt:
                constraints:
                    energy_cap_max: 30000 # increased to ensure no unmet_demand in first␣
↪timestep
    # region-1-end
    # other-locs-start
```

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```
    region2:
        coordinates: {lat: 40, lon: -8}
        techs:
            demand_power:
                constraints:
                    resource: file=demand-2.csv:demand
            battery:

    region1-1.coordinates: {lat: 41, lon: -2}
    region1-2.coordinates: {lat: 39, lon: -1}
    region1-3.coordinates: {lat: 39, lon: -2}

    region1-1, region1-2, region1-3:
        techs:
            csp:
    # other-locs-end

##
# TRANSMISSION CAPACITIES
##

links:
    # links-start
    region1,region2:
        techs:
            ac_transmission:
                constraints:
                    energy_cap_max: 10000
    region1,region1-1:
        techs:
            free_transmission:
    region1,region1-2:
        techs:
            free_transmission:
    region1,region1-3:
        techs:
            free_transmission:
    # links-end
```

Urban-scale example

Available as *calliope.examples.urban_scale*.

Model settings

model.yaml:

```yaml
import:  # Import other files from paths relative to this file, or absolute paths
    - 'model_config/techs.yaml'
    - 'model_config/locations.yaml'
    - 'scenarios.yaml'

model:
    name: Urban-scale example model

    # What version of Calliope this model is intended for
    calliope_version: 0.6.8

    # Time series data path - can either be a path relative to this file, or an absolute␣
↪path
    timeseries_data_path: 'timeseries_data'

    subset_time: ['2005-07-01', '2005-07-02']  # Subset of timesteps

run:
    mode: plan  # Choices: plan, operate

    solver: cbc

    ensure_feasibility: true # Switching on unmet demand

    bigM: 1e6 # setting the scale of unmet demand, which cannot be too high, otherwise␣
↪the optimisation will not converge

    objective_options.cost_class: {monetary: 1}
```

scenarios.yaml:

```yaml
##
# Overrides for different example model configuratiions
##

overrides:
    milp:
        model.name: 'Urban-scale example model with MILP'
        run.solver_options.mipgap: 0.05
        techs:
            # chp-start
            chp:
                constraints:
                    units_max: 4
                    energy_cap_per_unit: 300
                    energy_cap_min_use: 0.2
                costs:
                    monetary:
                        energy_cap: 700
```

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```
                    purchase: 40000
            # chp-end
            # boiler-start
            boiler:
                costs:
                    monetary:
                        energy_cap: 35
                        purchase: 2000
            # boiler-end
            # heat_pipes-start
            heat_pipes:
                constraints:
                    force_asynchronous_prod_con: true
            # heat_pipes-end

    mapbox_ready:
        locations:
            X1.coordinates: {lat: 51.4596158, lon: -0.1613446}
            X2.coordinates: {lat: 51.4652373, lon: -0.1141548}
            X3.coordinates: {lat: 51.4287016, lon: -0.1310635}
            N1.coordinates: {lat: 51.4450766, lon: -0.1247183}
        links:
            X1,X2.techs.power_lines.distance: 10
            X1,X3.techs.power_lines.distance: 5
            X1,N1.techs.heat_pipes.distance: 3
            N1,X2.techs.heat_pipes.distance: 3
            N1,X3.techs.heat_pipes.distance: 4

    operate:
        run.mode: operate
        run.operation:
            window: 24
            horizon: 48
        model.subset_time: ['2005-07-01', '2005-07-10']
        locations:
            X1:
                techs:
                    chp.constraints.energy_cap_max: 300
                    pv.constraints.energy_cap_max: 0
                    supply_grid_power.constraints.energy_cap_max: 40
                    supply_gas.constraints.energy_cap_max: 700

            X2:
                techs:
                    boiler.constraints.energy_cap_max: 200
                    pv.constraints.energy_cap_max: 70
                    supply_gas.constraints.energy_cap_max: 250

            X3:
                techs:
                    boiler.constraints.energy_cap_max: 0
                    pv.constraints.energy_cap_max: 50
```

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```
                    supply_gas.constraints.energy_cap_max: 0

        links:
            X1,X2.techs.power_lines.constraints.energy_cap_max: 300
            X1,X3.techs.power_lines.constraints.energy_cap_max: 60
            X1,N1.techs.heat_pipes.constraints.energy_cap_max: 300
            N1,X2.techs.heat_pipes.constraints.energy_cap_max: 250
            N1,X3.techs.heat_pipes.constraints.energy_cap_max: 320

    time_masking:
        model.name: 'Urban-scale example model with time masking'
        model.subset_time: '2005-01'
        # Resample time resolution to 6-hourly
        model.time:
            masks:
                - {function: extreme_diff, options: {tech0: demand_heat, tech1: demand_
↪electricity, how: max, n: 2}}
            function: resample
            function_options: {resolution: 6H}
```

techs.yaml:

```
##
# TECHNOLOGY DEFINITIONS
##

# Note: '-start' and '-end' is used in tutorial documentation only

# supply_power_plus-start
tech_groups:
    supply_power_plus:
        essentials:
            parent: supply_plus
            carrier: electricity
# supply_power_plus-end

techs:

##-GRID SUPPLY-##
    # supply-start
    supply_grid_power:
        essentials:
            name: 'National grid import'
            color: '#C5ABE3'
            parent: supply
            carrier: electricity
        constraints:
            resource: inf
            energy_cap_max: 2000
            lifetime: 25
        costs:
            monetary:
```

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```
                interest_rate: 0.10
                energy_cap: 15
                om_con: 0.1 # 10p/kWh electricity price #ppt

    supply_gas:
        essentials:
            name: 'Natural gas import'
            color: '#C98AAD'
            parent: supply
            carrier: gas
        constraints:
            resource: inf
            energy_cap_max: 2000
            lifetime: 25
        costs:
            monetary:
                interest_rate: 0.10
                energy_cap: 1
                om_con: 0.025 # 2.5p/kWh gas price #ppt
    # supply-end

##-Renewables-##
    # pv-start
    pv:
        essentials:
            name: 'Solar photovoltaic power'
            color: '#F9D956'
            parent: supply_power_plus
        constraints:
            export_carrier: electricity
            resource: file=pv_resource.csv:per_area  # Already accounts for panel␣
↪efficiency - kWh/m2. Source: Renewables.ninja Solar PV Power - Version: 1.1 - License:␣
↪https://creativecommons.org/licenses/by-nc/4.0/ - Reference: https://doi.org/10.1016/j.
↪energy.2016.08.060
            resource_unit: energy_per_area
            parasitic_eff: 0.85 # inverter losses
            energy_cap_max: 250
            resource_area_max: 1500
            force_resource: true
            resource_area_per_energy_cap: 7 # 7m2 of panels needed to fit 1kWp of panels
            lifetime: 25
        costs:
            monetary:
                interest_rate: 0.10
                energy_cap: 1350
    # pv-end

# Conversion
    # boiler-start
    boiler:
        essentials:
            name: 'Natural gas boiler'
```

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```
            color: '#8E2999'
            parent: conversion
            carrier_out: heat
            carrier_in: gas
        constraints:
            energy_cap_max: 600
            energy_eff: 0.85
            lifetime: 25
        costs:
            monetary:
                interest_rate: 0.10
                om_con: 0.004  # .4p/kWh
    # boiler-end

# Conversion_plus
    # chp-start
    chp:
        essentials:
            name: 'Combined heat and power'
            color: '#E4AB97'
            parent: conversion_plus
            primary_carrier_out: electricity
            carrier_in: gas
            carrier_out: electricity
            carrier_out_2: heat
        constraints:
            export_carrier: electricity
            energy_cap_max: 1500
            energy_eff: 0.405
            carrier_ratios.carrier_out_2.heat: 0.8
            lifetime: 25
        costs:
            monetary:
                interest_rate: 0.10
                energy_cap: 750
                om_prod: 0.004  # .4p/kWh for 4500 operating hours/year
                export: file=export_power.csv
    # chp-end

##-DEMAND-##
    # demand-start
    demand_electricity:
        essentials:
            name: 'Electrical demand'
            color: '#072486'
            parent: demand
            carrier: electricity

    demand_heat:
        essentials:
            name: 'Heat demand'
            color: '#660507'
```

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```
            parent: demand
            carrier: heat
    # demand-end

##-DISTRIBUTION-##
    # transmission-start
    power_lines:
        essentials:
            name: 'Electrical power distribution'
            color: '#6783E3'
            parent: transmission
            carrier: electricity
        constraints:
            energy_cap_max: 2000
            energy_eff: 0.98
            lifetime: 25
        costs:
            monetary:
                interest_rate: 0.10
                energy_cap_per_distance: 0.01

    heat_pipes:
        essentials:
            name: 'District heat distribution'
            color: '#823739'
            parent: transmission
            carrier: heat
        constraints:
            energy_cap_max: 2000
            energy_eff_per_distance: 0.975
            lifetime: 25
        costs:
            monetary:
                interest_rate: 0.10
                energy_cap_per_distance: 0.3
    # transmission-end
```

locations.yaml:

```
locations:
    # X1-start
    X1:
        techs:
            chp:
            pv:
            supply_grid_power:
                costs.monetary.energy_cap: 100 # cost of transformers
            supply_gas:
            demand_electricity:
                constraints.resource: file=demand_power.csv
            demand_heat:
                constraints.resource: file=demand_heat.csv
```

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```
        available_area: 500
        coordinates: {x: 2, y: 7}
    # X1-end
    # other-locs-start
    X2:
        techs:
            boiler:
                costs.monetary.energy_cap: 43.1 # different boiler costs
            pv:
                costs.monetary:
                        om_prod: -0.0203 # revenue for just producing electricity
                        export: -0.0491 # FIT return for PV export
            supply_gas:
            demand_electricity:
                constraints.resource: file=demand_power.csv
            demand_heat:
                constraints.resource: file=demand_heat.csv
        available_area: 1300
        coordinates: {x: 8, y: 7}

    X3:
        techs:
            boiler:
                costs.monetary.energy_cap: 78 # different boiler costs
            pv:
                constraints:
                    energy_cap_max: 50 # changing tariff structure below 50kW
                costs.monetary:
                        om_annual: -80.5 # reimbursement per kWp from FIT
            supply_gas:
            demand_electricity:
                constraints.resource: file=demand_power.csv
            demand_heat:
                constraints.resource: file=demand_heat.csv
        available_area: 900
        coordinates: {x: 5, y: 3}
    # other-locs-end
    # N1-start
    N1: # location for branching heat transmission network
        coordinates: {x: 5, y: 7}
    # N1-end

links:
    # links-start
    X1,X2:
        techs:
            power_lines:
                distance: 10
    X1,X3:
        techs:
            power_lines:
    X1,N1:
```

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```
        techs:
            heat_pipes:
    N1,X2:
        techs:
            heat_pipes:
    N1,X3:
        techs:
            heat_pipes:
    # links-end
```

1.11.2 Configuration reference

Configuration layout

There must always be at least one model configuration YAML file, probably called `model.yaml` or similar. This file can import any number of additional files.

This file or this set of files must specify the following top-level configuration keys:

- `name`: the name of the model
- `model`: model settings
- `run`: run settings
- `techs`: technology definitions
- (optionally) `tech_groups`: tech group definitions
- `locations`: location definitions
- (optionally) `links`: transmission link definitions

Note: Model settings (`model`) affect how the model and its data are built by Calliope, while run settings (`run`) only take effect once a built model is run (e.g. interactively via `model.run()`). This means that run settings, unlike model settings, can be updated after a model is built and before it is run, by modifying attributes in the built model dataset.

YAML configuration file format

All configuration files (with the exception of time series data files) are in the YAML format, "a human friendly data serialisation standard for all programming languages".

Configuration for Calliope is usually specified as `option: value` entries, where `value` might be a number, a text string, or a list (e.g. a list of further settings).

Calliope allows an abbreviated form for long, nested settings:

```
one:
   two:
      three: x
```

can be written as:

```
one.two.three: x
```

Calliope also allows a special `import:` directive in any YAML file. This can specify one or several YAML files to import. If both the imported file and the current file define the same option, the definition in the current file takes precedence.

Using quotation marks (' or ") to enclose strings is optional, but can help with readability. The three ways of setting `option` to `text` below are equivalent:

```
option: "text"
option: 'text'
option: text
```

Sometimes, a setting can be either enabled or disabled, in this case, the boolean values `true` or `false` are used.

Comments can be inserted anywhere in YAML files with the # symbol. The remainder of a line after # is interpreted as a comment.

See the YAML website for more general information about YAML.

Calliope internally represents the configuration as *AttrDict*s, which are a subclass of the built-in Python dictionary data type (`dict`) with added functionality such as YAML reading/writing and attribute access to keys.

1.11.3 Mathematical formulation

This section details the mathematical formulation of the different components. For each component, a link to the actual implementing function in the Calliope code is given.

Note: Make sure to also refer to the detailed *listing of constraints and costs along with their units and default values*.

Decision variables

`calliope.backend.pyomo.variables.`**`initialize_decision_variables`**(*backend_model*)

Defines decision variables.

Variable	Dimensions
energy_cap	loc_techs
carrier_prod	loc_tech_carriers_prod, timesteps
carrier_con	loc_tech_carriers_con, timesteps
cost	costs, loc_techs_cost
resource_area	loc_techs_area,
storage_cap	loc_techs_store
storage	loc_techs_store, timesteps
resource_con	loc_techs_supply_plus, timesteps
resource_cap	loc_techs_supply_plus
carrier_export	loc_tech_carriers_export, timesteps
cost_var	costs, loc_techs_om_cost, timesteps
cost_investment	costs, loc_techs_investment_cost
purchased	loc_techs_purchase
units	loc_techs_milp
operating_units	loc_techs_milp, timesteps
unmet_demand	loc_carriers, timesteps
unused_supply	loc_carriers, timesteps

Objective functions

calliope.backend.pyomo.objective.**minmax_cost_optimization**(*backend_model*)

Minimize or maximise total system cost for specified cost class or a set of cost classes. cost_class is a string or dictionary. If a string, it is automatically converted to a dictionary with a single key:value pair where value == 1. The dictionary provides a weight for each cost class of interest: {cost_1: weight_1, cost_2: weight_2, etc.}.

If unmet_demand is in use, then the calculated cost of unmet_demand is added or subtracted from the total cost in the opposite sense to the objective.

$$min: z = \sum_{loc::tech_{cost},k} (cost(loc :: tech, cost = cost_k) \times weight_k) + \sum_{loc::carrier,timestep} (unmet\_demand(loc :: carrier, time$$

$$max: z = \sum_{loc::tech_{cost},k} (cost(loc :: tech, cost = cost_k) \times weight_k) - \sum_{loc::carrier,timestep} (unmet\_demand(loc :: carrier, time$$

calliope.backend.pyomo.objective.**check_feasibility**(*backend_model*)

Dummy objective, to check that there are no conflicting constraints.

$$min: z = 1$$

Constraints

Energy Balance

calliope.backend.pyomo.constraints.energy_balance.**system_balance_constraint_rule**(*backend_model*, *loc_carrier*, *timestep*)

System balance ensures that, within each location, the production and consumption of each carrier is balanced.

$$\sum_{loc::tech::carrier_{prod} \in loc::carrier} \boldsymbol{carrier_{prod}}(loc :: tech :: carrier, timestep) + \sum_{loc::tech::carrier_{con} \in loc::carrier} \boldsymbol{carrier_{con}}(loc$$

calliope.backend.pyomo.constraints.energy_balance.**balance_supply_constraint_rule**(*backend_model*, *loc_tech*, *timestep*)

Limit production from supply techs to their available resource

$$min\_use(loc :: tech) \times available\_resource(loc :: tech, timestep) \leq \frac{\boldsymbol{carrier_{prod}}(loc :: tech :: carrier, timestep)}{\eta_{energy}(loc :: tech, timestep)} \geq avai$$

If $force\_resource(loc :: tech)$ is set:

$$\frac{\boldsymbol{carrier_{prod}}(loc :: tech :: carrier, timestep)}{\eta_{energy}(loc :: tech, timestep)} = available\_resource(loc :: tech, timestep) \quad \forall loc :: tech \in loc :: techs_{supp}$$

Where:

$$available\_resource(loc :: tech, timestep) = resource(loc :: tech, timestep) \times resource\_scale(loc :: tech)$$

if $loc :: tech$ is in $loc :: techs_{area}$:

$$available\_resource(loc :: tech, timestep) = resource(loc :: tech, timestep) \times resource\_scale(loc :: tech) \times \boldsymbol{resource_{are}}$$

calliope.backend.pyomo.constraints.energy_balance.**balance_demand_constraint_rule**(*backend_model*, *loc_tech*, *timestep*)

Limit consumption from demand techs to their required resource.

$$\boldsymbol{carrier_{con}}(loc :: tech :: carrier, timestep) \times \eta_{energy}(loc :: tech, timestep) \geq required\_resource(loc :: tech, timestep)$$

If $force\_resource(loc :: tech)$ is set:

$$\boldsymbol{carrier_{con}}(loc :: tech :: carrier, timestep) \times \eta_{energy}(loc :: tech, timestep) = required\_resource(loc :: tech, timestep)$$

Where:

$$required\_resource(loc :: tech, timestep) = resource(loc :: tech, timestep) \times resource\_scale(loc :: tech)$$

if $loc :: tech$ is in $loc :: techs_{area}$:

$$required\_resource(loc :: tech, timestep) = resource(loc :: tech, timestep) \times resource\_scale(loc :: tech) \times \boldsymbol{resource_{are}}$$

calliope.backend.pyomo.constraints.energy_balance.**resource_availability_supply_plus_constraint_rule**(*back*
*loc_*
time

Limit production from supply_plus techs to their available resource.

$$\boldsymbol{resource_{con}}(loc :: tech, timestep) \leq available\_resource(loc :: tech, timestep) \quad \forall loc :: tech \in loc :: techs_{supply^+}, \forall time$$

If $force\_resource(loc :: tech)$ is set:

$$\boldsymbol{resource_{con}}(loc :: tech, timestep) = available\_resource(loc :: tech, timestep) \quad \forall loc :: tech \in loc :: techs_{supply^+}, \forall time$$

Where:

$$available\_resource(loc :: tech, timestep) = resource(loc :: tech, timestep) \times resource_{scale}(loc :: tech)$$

if $loc :: tech$ is in $loc :: techs_{area}$:

$$available\_resource(loc :: tech, timestep) = resource(loc :: tech, timestep) \times resource_{scale}(loc :: tech) \times resource_{area}(lo$$

calliope.backend.pyomo.constraints.energy_balance.**balance_transmission_constraint_rule**(*backend_model*,
loc_tech,
timestep)

Balance carrier production and consumption of transmission technologies

$$-1 * \boldsymbol{carrier_{con}}(loc_{from} :: tech : loc_{to} :: carrier, timestep) \times \eta_{energy}(loc :: tech, timestep) = \boldsymbol{carrier_{prod}}(loc_{to} :: tech$$

Where a link is the connection between $loc_{from} :: tech : loc_{to}$ and $loc_{to} :: tech : loc_{from}$ for locations *to* and *from*.

calliope.backend.pyomo.constraints.energy_balance.**balance_supply_plus_constraint_rule**(*backend_model*,
loc_tech,
timestep)

Balance carrier production and resource consumption of supply_plus technologies alongside any use of resource storage.

$$\boldsymbol{storage}(loc :: tech, timestep) = \boldsymbol{storage}(loc :: tech, timestep_{previous}) \times (1 - storage\_loss(loc :: tech, timestep))^{timest}$$

If *no* storage is defined for the technology, this reduces to:

$$\boldsymbol{resource_{con}}(loc :: tech, timestep) \times \eta_{resource}(loc :: tech, timestep) = \frac{\boldsymbol{carrier_{prod}}(loc :: tech :: carrier, time}{\eta_{energy}(loc :: tech, timestep) \times \eta_{parasitic}(loc :: te}$$

calliope.backend.pyomo.constraints.energy_balance.**balance_storage_constraint_rule**(*backend_model*, *loc_tech*, *timestep*)

Balance carrier production and consumption of storage technologies, alongside any use of the stored volume.

$$\boldsymbol{storage}(loc :: tech, timestep) = \boldsymbol{storage}(loc :: tech, timestep_{previous}) \times (1 - storage\_loss(loc :: tech, timestep))^{resolut}$$

calliope.backend.pyomo.constraints.energy_balance.**balance_storage_inter_cluster_rule**(*backend_model*, *loc_tech*, *datestep*)

When clustering days, to reduce the timeseries length, balance the daily stored energy across all days of the original timeseries.

Ref: DOI 10.1016/j.apenergy.2018.01.023

$$\boldsymbol{storage_{inter\_cluster}}(loc :: tech, datestep) = \boldsymbol{storage_{inter\_cluster}}(loc :: tech, datestep_{previous}) \times (1 - storage\_loss(loc$$

Where $timestep_{final,cluster(datestep_{previous}))}$ is the final timestep of the cluster in the clustered timeseries corresponding to the previous day

calliope.backend.pyomo.constraints.energy_balance.**storage_initial_rule**(*backend_model*, *loc_tech*)

If storage is cyclic, allow an initial storage to still be set. This is applied to the storage of the final timestep/datestep of the series as that, in cyclic storage, is the 'storage_previous_step' for the first timestep/datestep.

If clustering and `storage_inter_cluster` exists:

$$\boldsymbol{storage_{inter\_cluster}}(loc :: tech, datestep_{final}) \times ((1 - storage_loss) * *24) = storage_{initial}(loc :: tech) \times storage_{cap}(loc$$

Where $datestep_{final}$ is the last datestep of the timeseries

Else: .. container:: scrolling-wrapper

$$\boldsymbol{storage}(loc :: tech, timestep_{final}) \times ((1 - storage_loss) * *24) = storage_{initial}(loc :: tech) \times storage_{cap}(loc :: tech$$

Where $timestep_{final}$ is the last timestep of the timeseries

Capacity

calliope.backend.pyomo.constraints.capacity.**storage_capacity_constraint_rule**(*backend_model*, *loc_tech*)

Set maximum storage capacity. Supply_plus & storage techs only

The first valid case is applied:

$$\boldsymbol{storage_{cap}}(loc :: tech) \begin{cases} = storage_{cap,equals}(loc :: tech), & \text{if } storage_{cap,equals}(loc :: tech) \\ \leq storage_{cap,max}(loc :: tech), & \text{if } storage_{cap,max}(loc :: tech) \quad \forall loc :: tech \in loc :: techs_{store} \\ \text{unconstrained}, & \text{otherwise} \end{cases}$$

and (if `equals` not enforced):

$$\boldsymbol{storage_{cap}}(loc :: tech) \geq storage_{cap,min}(loc :: tech) \quad \forall loc :: tech \in loc :: techs_{store}$$

calliope.backend.pyomo.constraints.capacity.**energy_capacity_storage_constraint_rule_old**(*backend_model*, *loc_tech*)

Set an additional energy capacity constraint on storage technologies, based on their use of *charge_rate*.

This is deprecated and will be removed in Calliope 0.7.0. Instead of *charge_rate*, please use *energy_cap_per_storage_cap_max*.

$$\boldsymbol{energy_{cap}}(loc :: tech) \leq \boldsymbol{storage_{cap}}(loc :: tech) \times charge\_rate(loc :: tech) \quad \forall loc :: tech \in loc :: techs_{store}$$

calliope.backend.pyomo.constraints.capacity.**energy_capacity_storage_min_constraint_rule**(*backend_model*, *loc_tech*)

Limit energy capacities of storage technologies based on their storage capacities.

$$\boldsymbol{energy_{cap}}(loc :: tech) \geq \boldsymbol{storage_{cap}}(loc :: tech) \times energy\_cap\_per\_storage\_cap\_min(loc :: tech)$$
$$\forall loc :: tech \in loc :: techs_{store}$$

calliope.backend.pyomo.constraints.capacity.**energy_capacity_storage_max_constraint_rule**(*backend_model*, *loc_tech*)

Limit energy capacities of storage technologies based on their storage capacities.

$$\boldsymbol{energy_{cap}}(loc :: tech) \leq \boldsymbol{storage_{cap}}(loc :: tech) \times energy\_cap\_per\_storage\_cap\_max(loc :: tech)$$
$$\forall loc :: tech \in loc :: techs_{store}$$

calliope.backend.pyomo.constraints.capacity.**energy_capacity_storage_equals_constraint_rule**(*backend_model*, *loc_tech*)

Limit energy capacities of storage technologies based on their storage capacities.

$$\boldsymbol{energy_{cap}}(loc :: tech) = \boldsymbol{storage_{cap}}(loc :: tech) \times energy\_cap\_per\_storage\_cap\_equals(loc :: tech) \forall loc :: tech \in loc ::$$

calliope.backend.pyomo.constraints.capacity.**resource_capacity_constraint_rule**(*backend_model*, *loc_tech*)

Add upper and lower bounds for resource_cap.

The first valid case is applied:

$$\boldsymbol{resource_{cap}}(loc :: tech) \begin{cases} = resource_{cap,equals}(loc :: tech), & \text{if } resource_{cap,equals}(loc :: tech) \\ \leq resource_{cap,max}(loc :: tech), & \text{if } resource_{cap,max}(loc :: tech) \quad \forall loc :: tech \in loc :: techs_{f} \\ \text{unconstrained}, & \text{otherwise} \end{cases}$$

and (if `equals` not enforced):

$$\boldsymbol{resource_{cap}}(loc :: tech) \geq resource_{cap,min}(loc :: tech) \quad \forall loc :: tech \in loc :: techs_{finite\_resource\_supply\_plus}$$

calliope.backend.pyomo.constraints.capacity.**resource_capacity_equals_energy_capacity_constraint_rule**(*bac*
loc

Add equality constraint for resource_cap to equal energy_cap, for any technologies which have defined resource_cap_equals_energy_cap.

$$\boldsymbol{resource_{cap}}(loc :: tech) = \boldsymbol{energy_{cap}}(loc :: tech) \quad \forall loc :: tech \in loc :: techs_{finite\_resource\_supply\_plus} \text{ if } resource\_cap\_$$

calliope.backend.pyomo.constraints.capacity.**resource_area_constraint_rule**(*backend_model*, *loc_tech*)

Set upper and lower bounds for resource_area.

The first valid case is applied:

$$\boldsymbol{resource_{area}}(loc :: tech) \begin{cases} = resource_{area,equals}(loc :: tech), & \text{if } resource_{area,equals}(loc :: tech) \\ \leq resource_{area,max}(loc :: tech), & \text{if } resource_{area,max}(loc :: tech) \quad \forall loc :: tech \in loc :: tec \\ \text{unconstrained}, & \text{otherwise} \end{cases}$$

and (if `equals` not enforced):

$$\boldsymbol{resource_{area}}(loc :: tech) \geq resource_{area,min}(loc :: tech) \quad \forall loc :: tech \in loc :: techs_{area}$$

calliope.backend.pyomo.constraints.capacity.**resource_area_per_energy_capacity_constraint_rule**(*backend_mo*
loc_tech)

Add equality constraint for resource_area to equal a percentage of energy_cap, for any technologies which have defined resource_area_per_energy_cap

$$\boldsymbol{resource_{area}}(loc :: tech) = \boldsymbol{energy_{cap}}(loc :: tech) \times area\_per\_energy\_cap(loc :: tech) \quad \forall loc :: tech \in locs :: techs_{are}$$

calliope.backend.pyomo.constraints.capacity.**resource_area_capacity_per_loc_constraint_rule**(*backend_model*,
loc)

Set upper bound on use of area for all locations which have *available_area* constraint set. Does not consider resource_area applied to demand technologies

$$\sum_{tech} \boldsymbol{resource_{area}}(loc :: tech) \leq available\_area \quad \forall loc \in locs \text{ if } available\_area(loc)$$

calliope.backend.pyomo.constraints.capacity.**energy_capacity_constraint_rule**(*backend_model*, *loc_tech*)

Set upper and lower bounds for energy_cap.

The first valid case is applied:

$$\frac{\boldsymbol{energy_{cap}}(loc :: tech)}{energy_{cap,scale}(loc :: tech)} \begin{cases} = energy_{cap,equals}(loc :: tech), & \text{if } energy_{cap,equals}(loc :: tech) \\ \leq energy_{cap,max}(loc :: tech), & \text{if } energy_{cap,max}(loc :: tech) \quad \forall loc :: tech \in loc :: techs \\ \text{unconstrained}, & \text{otherwise} \end{cases}$$

and (if `equals` not enforced):

$$\frac{\boldsymbol{energy_{cap}}(loc :: tech)}{energy_{cap,scale}(loc :: tech)} \geq energy_{cap,min}(loc :: tech) \quad \forall loc :: tech \in loc :: techs$$

`calliope.backend.pyomo.constraints.capacity.`**`energy_capacity_systemwide_constraint_rule`**(*backend_model*, *tech*)

Set constraints to limit the capacity of a single technology type across all locations in the model.

The first valid case is applied:

$$\sum_{loc} \boldsymbol{energy_{cap}}(loc :: tech) \begin{cases} = energy_{cap,equals,systemwide}(loc :: tech), & \text{if } energy_{cap,equals,systemwide}(loc :: tech) \\ \leq energy_{cap,max,systemwide}(loc :: tech), & \text{if } energy_{cap,max,systemwide}(loc :: tech) \quad \forall tech \in \\ \text{unconstrained}, & \text{otherwise} \end{cases}$$

Dispatch

`calliope.backend.pyomo.constraints.dispatch.`**`carrier_production_max_constraint_rule`**(*backend_model*, *loc_tech_carrier*, *timestep*)

Set maximum carrier production. All technologies.

$$\boldsymbol{carrier_{prod}}(loc :: tech :: carrier, timestep) \leq energy_{cap}(loc :: tech) \times timestep\_resolution(timestep) \times parasitic\_eff$$

`calliope.backend.pyomo.constraints.dispatch.`**`carrier_production_min_constraint_rule`**(*backend_model*, *loc_tech_carrier*, *timestep*)

Set minimum carrier production. All technologies except `conversion_plus`.

$$\boldsymbol{carrier_{prod}}(loc :: tech :: carrier, timestep) \geq energy_{cap}(loc :: tech) \times timestep\_resolution(timestep) \times energy_{cap,min}$$

`calliope.backend.pyomo.constraints.dispatch.`**`carrier_consumption_max_constraint_rule`**(*backend_model*, *loc_tech_carrier*, *timestep*)

Set maximum carrier consumption for demand, storage, and transmission techs.

$$\boldsymbol{carrier_{con}}(loc :: tech :: carrier, timestep) \geq -1 \times energy_{cap}(loc :: tech) \times timestep\_resolution(timestep)$$

`calliope.backend.pyomo.constraints.dispatch.`**`resource_max_constraint_rule`**(*backend_model*, *loc_tech*, *timestep*)

Set maximum resource consumed by supply_plus techs.

$$\boldsymbol{resource_{con}}(loc :: tech, timestep) \leq timestep\_resolution(timestep) \times resource_{cap}(loc :: tech)$$

calliope.backend.pyomo.constraints.dispatch.**storage_max_constraint_rule**(*backend_model*, *loc_tech*, *timestep*)

Set maximum stored energy. Supply_plus & storage techs only.

$$\boldsymbol{storage}(loc :: tech, timestep) \leq storage_{cap}(loc :: tech)$$

calliope.backend.pyomo.constraints.dispatch.**storage_discharge_depth_constraint_rule**(*backend_model*, *loc_tech*, *timestep*)

Forces storage state of charge to be greater than the allowed depth of discharge.

$$\boldsymbol{storage}(loc :: tech, timestep) >= \boldsymbol{storage_{discharge_depth}} \forall loc :: tech \in loc :: techs_{storage}, \forall timestep \in timesteps$$

calliope.backend.pyomo.constraints.dispatch.**ramping_up_constraint_rule**(*backend_model*, *loc_tech_carrier*, *timestep*)

Ramping up constraint.

$$diff(loc :: tech :: carrier, timestep) \leq max\_ramping\_rate(loc :: tech :: carrier, timestep)$$

calliope.backend.pyomo.constraints.dispatch.**ramping_down_constraint_rule**(*backend_model*, *loc_tech_carrier*, *timestep*)

Ramping down constraint.

$$-1 \times max\_ramping\_rate(loc :: tech :: carrier, timestep) \leq diff(loc :: tech :: carrier, timestep)$$

calliope.backend.pyomo.constraints.dispatch.**ramping_constraint**(*backend_model*, *loc_tech_carrier*, *timestep*, *direction=0*)

Ramping rate constraints.

Direction: 0 is up, 1 is down.

$$\boldsymbol{diff}(loc :: tech :: carrier, timestep) = (carrier_{prod}(loc :: tech :: carrier, timestep) + carrier_{con}(loc :: tech :: carrier, ti$$

calliope.backend.pyomo.constraints.dispatch.**storage_intra_max_rule**(*backend_model*, *loc_tech*, *timestep*)

When clustering days, to reduce the timeseries length, set limits on intra-cluster auxiliary maximum storage decision variable. Ref: DOI 10.1016/j.apenergy.2018.01.023

$$\boldsymbol{storage}(loc :: tech, timestep) \leq \boldsymbol{storage_{intra\_cluster,max}}(loc :: tech, cluster(timestep)) \quad \forall loc :: tech \in loc :: techs_{sto}$$

Where $cluster(timestep)$ is the cluster number in which the timestep is located.

calliope.backend.pyomo.constraints.dispatch.**storage_intra_min_rule**(*backend_model*, *loc_tech*, *timestep*)

When clustering days, to reduce the timeseries length, set limits on intra-cluster auxiliary minimum storage decision variable. Ref: DOI 10.1016/j.apenergy.2018.01.023

$$\boldsymbol{storage}(loc::tech, timestep) \geq \boldsymbol{storage_{intra\_cluster,min}}(loc::tech, cluster(timestep)) \quad \forall loc::tech \in loc::techs_{sto}$$

Where $cluster(timestep)$ is the cluster number in which the timestep is located.

calliope.backend.pyomo.constraints.dispatch.**storage_inter_max_rule**(*backend_model*, *loc_tech*, *datestep*)

When clustering days, to reduce the timeseries length, set maximum limit on the intra-cluster and inter-date stored energy. intra-cluster = all timesteps in a single cluster datesteps = all dates in the unclustered timeseries (each has a corresponding cluster) Ref: DOI 10.1016/j.apenergy.2018.01.023

$$\boldsymbol{storage_{inter\_cluster}}(loc::tech, datestep) + \boldsymbol{storage_{intra\_cluster,max}}(loc::tech, cluster(datestep)) \leq \boldsymbol{storage_{cap}}(lo$$

Where $cluster(datestep)$ is the cluster number in which the datestep is located.

calliope.backend.pyomo.constraints.dispatch.**storage_inter_min_rule**(*backend_model*, *loc_tech*, *datestep*)

When clustering days, to reduce the timeseries length, set minimum limit on the intra-cluster and inter-date stored energy. intra-cluster = all timesteps in a single cluster datesteps = all dates in the unclustered timeseries (each has a corresponding cluster) Ref: DOI 10.1016/j.apenergy.2018.01.023

$$\boldsymbol{storage_{inter\_cluster}}(loc::tech, datestep) \times (1 - storage\_loss(loc::tech, timestep))^{24} + \boldsymbol{storage_{intra\_cluster,min}}(loc$$

Where $cluster(datestep)$ is the cluster number in which the datestep is located.

Costs

calliope.backend.pyomo.constraints.costs.**cost_constraint_rule**(*backend_model*, *cost*, *loc_tech*)

Combine investment and time varying costs into one cost per technology.

$$\boldsymbol{cost}(cost, loc::tech) = \boldsymbol{cost_{investment}}(cost, loc::tech) + \sum_{timestep \in timesteps} \boldsymbol{cost_{var}}(cost, loc::tech, timestep)$$

calliope.backend.pyomo.constraints.costs.**cost_investment_constraint_rule**(*backend_model*, *cost*, *loc_tech*)

Calculate costs from capacity decision variables.

Transmission technologies "exist" at two locations, so their cost is divided by 2.

$$cost_{cap}(cost, loc::tech) = depreciation\_rate * ts\_weight * (cost_{energy\_cap}(cost, loc::tech) \times \boldsymbol{energy_{cap}}(loc::tech) + c$$

calliope.backend.pyomo.constraints.costs.**cost_var_constraint_rule**(*backend_model*, *cost*, *loc_tech*, *timestep*)

Calculate costs from time-varying decision variables

$$\boldsymbol{cost_{var}}(cost, loc :: tech, timestep) = cost_{prod}(cost, loc :: tech, timestep) + cost_{con}(co$$

$$cost_{prod}(cost, loc :: tech, timestep) = cost_{om\_prod}(cost, loc :: tech, timestep) \times weight(timestep) \times \boldsymbol{carrier_{prod}}(loc :: te$$

$$prod\_con\_eff = \begin{cases} = \boldsymbol{resource_{con}}(loc :: tech, timestep), & \text{if } loc :: tech \in \\ = \frac{\boldsymbol{carrier_{prod}}(loc::tech::carrier, timestep)}{energy_eff(loc::tech, timestep)}, & \text{if } loc :: tech \in \end{cases}$$

$$cost_{con}(cost, loc :: tech, timestep) = cost_{om\_con}(cost, loc :: tech, timestep) \times weight(tim$$

Export

calliope.backend.pyomo.constraints.export.**update_system_balance_constraint**(*backend_model*, *loc_carrier*, *timestep*)

Update system balance constraint (from energy_balance.py) to include export

Math given in *system_balance_constraint_rule()*

calliope.backend.pyomo.constraints.export.**export_balance_constraint_rule**(*backend_model*, *loc_tech_carrier*, *timestep*)

Ensure no technology can 'pass' its export capability to another technology with the same carrier_out, by limiting its export to the capacity of its production

$$\boldsymbol{carrier_{prod}}(loc :: tech :: carrier, timestep) \geq \boldsymbol{carrier_{export}}(loc :: tech :: carrier, timestep) \quad \forall loc :: tech :: carrier \in$$

calliope.backend.pyomo.constraints.export.**update_costs_var_constraint**(*backend_model*, *cost*, *loc_tech*, *timestep*)

Update time varying cost constraint (from costs.py) to include export

$$\boldsymbol{cost_{var}}(cost, loc :: tech, timestep) += cost_{export}(cost, loc :: tech, timestep) \times \boldsymbol{carrier_{export}}(loc :: tech :: carrier, time$$

calliope.backend.pyomo.constraints.export.**export_max_constraint_rule**(*backend_model*, *loc_tech_carrier*, *timestep*)

Set maximum export. All exporting technologies.

$$\boldsymbol{carrier_{export}}(loc :: tech :: carrier, timestep) \leq export_{cap}(loc :: tech) \quad \forall loc :: tech :: carrier \in locs :: tech :: carriers_{ex}$$

If the technology is defined by integer units, not a continuous capacity, this constraint becomes:

$$\boldsymbol{carrier_{export}}(loc :: tech :: carrier, timestep) \leq export_{cap}(loc :: tech) \times \boldsymbol{operating_{units}}(loc :: tech, timestep)$$

MILP

calliope.backend.pyomo.constraints.milp.**unit_commitment_milp_constraint_rule**(*backend_model*, *loc_tech*, *timestep*)

Constraining the number of integer units $operating_units(loc_tech, timestep)$ of a technology which can operate in a given timestep, based on maximum purchased units $units(loc_tech)$

$$\boldsymbol{operating\_units}(loc :: tech, timestep) \leq \boldsymbol{units}(loc :: tech) \quad \forall loc :: tech \in loc :: techs_{milp}, \forall timestep \in timesteps$$

calliope.backend.pyomo.constraints.milp.**unit_capacity_milp_constraint_rule**(*backend_model*, *loc_tech*)

Add upper and lower bounds for purchased units of a technology

$$\boldsymbol{units}(loc :: tech) \begin{cases} = units_{equals}(loc :: tech), & \text{if } units_{equals}(loc :: tech) \\ \leq units_{max}(loc :: tech), & \text{if } units_{max}(loc :: tech) \\ \text{unconstrained}, & \text{otherwise} \end{cases} \quad \forall loc :: tech \in loc :: techs_{milp}$$

and (if `equals` not enforced):

$$\boldsymbol{units}(loc :: tech) \geq units_{min}(loc :: tech) \quad \forall loc :: tech \in loc :: techs_{milp}$$

calliope.backend.pyomo.constraints.milp.**carrier_production_max_milp_constraint_rule**(*backend_model*, *loc_tech_carrier*, *timestep*)

Set maximum carrier production of MILP techs that aren't conversion plus

$$\boldsymbol{carrier_{prod}}(loc :: tech :: carrier, timestep) \leq energy_{cap,perunit}(loc :: tech) \times timestep\_resolution(timestep) \times \boldsymbol{opera}$$

$\eta_{parasitic}$ is only activated for *supply_plus* technologies

calliope.backend.pyomo.constraints.milp.**carrier_production_max_conversion_plus_milp_constraint_rule**(*back*, *loc_*, *time*

Set maximum carrier production of conversion_plus MILP techs

$$\sum_{loc::tech::carrier \in loc::tech::carriers_{out}} \boldsymbol{carrier_{prod}}(loc :: tech :: carrier, timestep) \leq energy_{cap,perunit}(loc :: tech) \times timeste$$

calliope.backend.pyomo.constraints.milp.**carrier_production_min_milp_constraint_rule**(*backend_model*, *loc_tech_carrier*, *timestep*)

Set minimum carrier production of MILP techs that aren't conversion plus

$$\boldsymbol{carrier_{prod}}(loc :: tech :: carrier, timestep) \geq energy_{cap,perunit}(loc :: tech) \times timestep\_resolution(timestep) \times \boldsymbol{opera}$$

calliope.backend.pyomo.constraints.milp.**carrier_production_min_conversion_plus_milp_constraint_rule**(*back*
*loc_*
time

Set minimum carrier production of conversion_plus MILP techs

$$\sum_{loc::tech::carrier \in loc::tech::carriers_{out}} \boldsymbol{carrier_{prod}}(loc :: tech :: carrier, timestep) \geq energy_{cap,perunit}(loc :: tech) \times timeste$$

calliope.backend.pyomo.constraints.milp.**carrier_consumption_max_milp_constraint_rule**(*backend_model*,
loc_tech_carrier,
timestep)

Set maximum carrier consumption of demand, storage, and transmission MILP techs

$$\boldsymbol{carrier_{con}}(loc :: tech :: carrier, timestep) \geq -1 * energy_{cap,perunit}(loc :: tech) \times timestep\_resolution(timestep) \times \boldsymbol{op}$$

calliope.backend.pyomo.constraints.milp.**energy_capacity_units_milp_constraint_rule**(*backend_model*,
loc_tech)

Set energy capacity decision variable as a function of purchased units

$$\boldsymbol{energy_{cap}}(loc :: tech) = \boldsymbol{units}(loc :: tech) \times energy_{cap,perunit}(loc :: tech) \quad \forall loc :: tech \in loc :: techs_{milp}$$

calliope.backend.pyomo.constraints.milp.**storage_capacity_units_milp_constraint_rule**(*backend_model*,
loc_tech)

Set storage capacity decision variable as a function of purchased units

$$\boldsymbol{storage_{cap}}(loc :: tech) = \boldsymbol{units}(loc :: tech) \times storage_{cap,perunit}(loc :: tech) \quad \forall loc :: tech \in loc :: techs_{milp,store}$$

calliope.backend.pyomo.constraints.milp.**energy_capacity_max_purchase_milp_constraint_rule**(*backend_model*,
loc_tech)

Set maximum energy capacity decision variable upper bound as a function of binary purchase variable

The first valid case is applied:

$$\frac{\boldsymbol{energy_{cap}}(loc :: tech)}{energy_{cap,scale}(loc :: tech)} \begin{cases} = energy_{cap,equals}(loc :: tech) \times \boldsymbol{purchased}(loc :: tech), & \text{if } energy_{cap,equals}(loc :: tech) \\ \leq energy_{cap,max}(loc :: tech) \times \boldsymbol{purchased}(loc :: tech), & \text{if } energy_{cap,max}(loc :: tech) \quad \forall \\ \text{unconstrained}, & \text{otherwise} \end{cases}$$

calliope.backend.pyomo.constraints.milp.**energy_capacity_min_purchase_milp_constraint_rule**(*backend_model*,
loc_tech)

Set minimum energy capacity decision variable upper bound as a function of binary purchase variable

and (if `equals` not enforced):

$$\frac{\boldsymbol{energy_{cap}}(loc :: tech)}{energy_{cap,scale}(loc :: tech)} \geq energy_{cap,min}(loc :: tech) \times \boldsymbol{purchased}(loc :: tech) \quad \forall loc :: tech \in loc :: techs$$

calliope.backend.pyomo.constraints.milp.**storage_capacity_max_purchase_milp_constraint_rule**(*backend_model*, *loc_tech*)

Set maximum storage capacity.

The first valid case is applied:

$$\boldsymbol{storage_{cap}}(loc :: tech) \begin{cases} = storage_{cap,equals}(loc :: tech) \times \boldsymbol{purchased}, & \text{if } storage_{cap,equals} \\ \leq storage_{cap,max}(loc :: tech) \times \boldsymbol{purchased}, & \text{if } storage_{cap,max}(loc :: tech) \; \forall loc :: tech \in loc \\ \text{unconstrained}, & \text{otherwise} \end{cases}$$

calliope.backend.pyomo.constraints.milp.**storage_capacity_min_purchase_milp_constraint_rule**(*backend_model*, *loc_tech*)

Set minimum storage capacity decision variable as a function of binary purchase variable

if `equals` not enforced for storage_cap:

$$\boldsymbol{storage_{cap}}(loc :: tech) \geq storage_{cap,min}(loc :: tech) \times \boldsymbol{purchased}(loc :: tech) \quad \forall loc :: tech \in loc :: techs_{purchase,store}$$

calliope.backend.pyomo.constraints.milp.**update_costs_investment_units_milp_constraint**(*backend_model*, *cost*, *loc_tech*)

Add MILP investment costs (cost * number of units purchased)

$$\boldsymbol{cost_{investment}}(cost, loc :: tech) += \boldsymbol{units}(loc :: tech) \times cost_{purchase}(cost, loc :: tech) * timestep_{weight} * depreciation$$

calliope.backend.pyomo.constraints.milp.**update_costs_investment_purchase_milp_constraint**(*backend_model*, *cost*, *loc_tech*)

Add binary investment costs (cost * binary_purchased_unit)

$$\boldsymbol{cost_{investment}}(cost, loc :: tech) += \boldsymbol{purchased}(loc :: tech) \times cost_{purchase}(cost, loc :: tech) * timestep_{weight} * depreci$$

calliope.backend.pyomo.constraints.milp.**unit_capacity_systemwide_milp_constraint_rule**(*backend_model*, *tech*)

Set constraints to limit the number of purchased units of a single technology type across all locations in the model.

The first valid case is applied:

$$\sum_{loc} \boldsymbol{units}(loc :: tech) + \boldsymbol{purchased}(loc :: tech) \begin{cases} = units_{equals,systemwide}(tech), & \text{if } units_{equals,systemwide}(tech) \\ \leq units_{max,systemwide}(tech), & \text{if } units_{max,systemwide}(tech) \quad \forall tech \\ \text{unconstrained}, & \text{otherwise} \end{cases}$$

calliope.backend.pyomo.constraints.milp.**asynchronous_con_milp_constraint_rule**(*backend_model*, *loc_tech*, *timestep*)

BigM limit set on *carrier_con*, forcing it to either be zero or non-zero, depending on whether *con* is zero or one, respectively.

$-\boldsymbol{carrier_{con}}[loc :: tech :: carrier, timestep] \leq \text{bigM} \times (1 - \boldsymbol{prod_{con}switch}[loc :: tech, timestep]) \forall loc :: tech \in loc ::$

calliope.backend.pyomo.constraints.milp.**asynchronous_prod_milp_constraint_rule**(*backend_model*, *loc_tech*, *timestep*)

BigM limit set on *carrier_prod*, forcing it to either be zero or non-zero, depending on whether *prod* is zero or one, respectively.

$\boldsymbol{carrier_{prod}}[loc :: tech :: carrier, timestep] \leq \text{bigM} \times \boldsymbol{prod_{con}switch}[loc :: tech, timestep] \forall loc :: tech \in loc :: techs_{a}$

Conversion

calliope.backend.pyomo.constraints.conversion.**balance_conversion_constraint_rule**(*backend_model*, *loc_tech*, *timestep*)

Balance energy carrier consumption and production

$-1 * \boldsymbol{carrier_{con}}(loc :: tech :: carrier, timestep) \times \eta_{energy}(loc :: tech, timestep) = \boldsymbol{carrier_{prod}}(loc :: tech :: carrier, ti$

calliope.backend.pyomo.constraints.conversion.**cost_var_conversion_constraint_rule**(*backend_model*, *cost*, *loc_tech*, *timestep*)

Add time-varying conversion technology costs

$\boldsymbol{cost_{var}}(loc :: tech, cost, timestep) = \boldsymbol{carrier_{prod}}(loc :: tech :: carrier, timestep) \times timestep_{weight}(timestep) \times cost_{om}$

Conversion_plus

calliope.backend.pyomo.constraints.conversion_plus.**balance_conversion_plus_primary_constraint_rule**(*backe*, *loc_te*, *timest*)

Balance energy carrier consumption and production for carrier_in and carrier_out

$$\sum_{loc::tech::carrier \in loc::tech::carriers_{out}} \frac{\boldsymbol{carrier_{prod}}(loc :: tech :: carrier, timestep)}{carrier\_ratio(loc :: tech :: carrier, \text{'}out\text{'})} = -1 * \sum_{loc::tech::carrier \in loc::tech::carriers_{in}} (c$$

calliope.backend.pyomo.constraints.conversion_plus.**carrier_production_max_conversion_plus_constraint_ru**

Set maximum conversion_plus carrier production.

$$\sum_{loc::tech::carrier \in loc::tech::carriers_{out}} \boldsymbol{carrier_{prod}}(loc :: tech :: carrier, timestep) \leq \boldsymbol{energy_{cap}}(loc :: tech) \times timestep\_res$$

calliope.backend.pyomo.constraints.conversion_plus.**carrier_production_min_conversion_plus_constraint_ru**

Set minimum conversion_plus carrier production.

$$\sum_{loc::tech::carrier \in loc::tech::carriers_{out}} \boldsymbol{carrier_{prod}}(loc :: tech :: carrier, timestep) \leq \boldsymbol{energy_{cap}}(loc :: tech) \times timestep\_res$$

calliope.backend.pyomo.constraints.conversion_plus.**cost_var_conversion_plus_constraint_rule**(*backend_mode*, *cost*, *loc_tech*, *timestep*)

Add time-varying conversion_plus technology costs

$$\boldsymbol{cost_{var}}(loc :: tech, cost, timestep) = \boldsymbol{carrier_{prod}}(loc :: tech :: carrier_{primary}, timestep) \times timestep_{weight}(timestep) \times$$

calliope.backend.pyomo.constraints.conversion_plus.**balance_conversion_plus_tiers_constraint_rule**(*backend*, *tier*, *loc_tech*, *timestep*)

Force all carrier_in_2/carrier_in_3 and carrier_out_2/carrier_out_3 to follow carrier_in and carrier_out (respectively).

If *tier* in ['out_2', 'out_3']:

$$\sum_{loc::tech::carrier \in loc::tech::carriers_{out}} (\frac{\boldsymbol{carrier_{prod}}(loc :: tech :: carrier, timestep)}{carrier\_ratio(loc :: tech :: carrier, `out')} = \sum_{loc::tech::carrier \in loc::tech::carriers_{tier}} (\frac{\boldsymbol{car}}{c}$$

If *tier* in ['in_2', 'in_3']:

$$\sum_{loc::tech::carrier \in loc::tech::carriers_{in}} \frac{\boldsymbol{carrier_{con}}(loc :: tech :: carrier, timestep)}{carrier\_ratio(loc :: tech :: carrier, `in')} = \sum_{loc::tech::carrier \in loc::tech::carriers_{tier}} \frac{\boldsymbol{carri}}{carr}$$

calliope.backend.pyomo.constraints.conversion_plus.**conversion_plus_prod_con_to_zero_constraint_rule**(*back*, *loc_*, *time*)

Force any carrier production or consumption for a conversion plus technology to zero in timesteps where its carrier_ratio is zero

Network

calliope.backend.pyomo.constraints.network.**symmetric_transmission_constraint_rule**(*backend_model*, *loc_tech*)

Constrain e_cap symmetrically for transmission nodes. Transmission techs only.

$$energy_{cap}(loc1 :: tech : loc2) = energy_{cap}(loc2 :: tech : loc1)$$

Policy

calliope.backend.pyomo.constraints.policy.**group_share_energy_cap_constraint_rule**(*backend_model*, *techlist*, *what*)

Enforce shares in energy_cap for groups of technologies. Applied to `supply` and `supply_plus` technologies only.

$$\sum_{loc::tech \in given\_group} energy_{cap}(loc :: tech) = fraction \times \sum_{loc::tech \in loc\_techs\_supply loc\_techs\_supply\_plus} energy_{cap}(loc :: tech)$$

calliope.backend.pyomo.constraints.policy.**group_share_carrier_prod_constraint_rule**(*backend_model*, *techlist_carrier*, *what*)

Enforce shares in carrier_prod for groups of technologies. Applied to `loc_tech_carriers_supply_conversion_all`, which includes supply, supply_plus, conversion, and conversion_plus.

$$\sum_{loc::tech::carrier \in given\_group, timestep \in timesteps} carrier_{prod}(loc :: tech :: carrier, timestep) = fraction \times$$
$$loc::tech:carrier \in loc\_te$$

calliope.backend.pyomo.constraints.policy.**reserve_margin_constraint_rule**(*backend_model*, *carrier*)

Enforces a system reserve margin per carrier.

$$\sum_{loc::tech::carrier \in loc\_tech\_carriers\_supply\_all} energy_{cap}(loc :: tech :: carrier, timestep_{max\_demand}) \geq \sum_{loc::tech::carrier \in loc\_tech\_ca}$$

Group constraints

calliope.backend.pyomo.constraints.group.**demand_share_constraint_rule**(*backend_model*, *group_name*, *what*)

Enforces shares of demand of a carrier to be met by the given groups of technologies at the given locations, on average over the entire model period. The share is relative to `demand` technologies only.

$$\sum_{loc::tech::carrier \in given\_group, timestep \in timesteps} carrier_{prod}(loc :: tech :: carrier, timestep) \leq share \times$$
$$loc::tech:carrier \in loc\_techs$$

calliope.backend.pyomo.constraints.group.**demand_share_per_timestep_constraint_rule**(*backend_model*, *group_name*, *timestep*, *what*)

Enforces shares of demand of a carrier to be met by the given groups of technologies at the given locations, in each timestep. The share is relative to `demand` technologies only.

$$\sum_{loc::tech::carrier \in given\_group} carrier_{prod}(loc :: tech :: carrier, timestep) \leq share \times \sum_{loc::tech:carrier \in loc\_techs\_demand \in given\_loca}$$

calliope.backend.pyomo.constraints.group.**demand_share_per_timestep_decision_main_constraint_rule**(*backend_model*, *group_name*, *loc_tech*, *timestep*, *sense*, *scale*)

Allows the model to decide on how a fraction demand for a carrier is met by the given groups, which will all have the same share in each timestep. The share is relative to the actual demand from `demand` technologies only.

The main constraint enforces that the shares are the same in each timestep.

$$\sum_{loc::tech::carrier \in given\_group} carrier_{prod}(loc :: tech :: carrier, timestep)$$
$$=$$
$$\sum_{loc::tech::carrier \in given\_group} required\_resource(loc :: tech :: carrier, timestep)$$
$$\times \sum_{loc::tech::carrier \in given\_group} demand\_share\_per\_timestep\_decision(loc :: tech :: carrier)$$
$$\forall timestep \in timesteps$$
$$\forall tech \in techs$$

calliope.backend.pyomo.constraints.group.**demand_share_per_timestep_decision_sum_constraint_rule**(*backend_model*, *group_name*)

Allows the model to decide on how a fraction of demand for a carrier is met by the given groups, which will all have the same share in each timestep. The share is relative to the actual demand from `demand` technologies only.

The sum constraint ensures that all decision shares add up to the share of carrier demand specified in the constraint.

This constraint is only applied if the share of carrier demand has been set to a not-None value.

$$share = \sum_{loc::tech::carrier \in given\_group} demand\_share\_per\_timestep\_decision(loc :: tech :: carrier)$$

calliope.backend.pyomo.constraints.group.**carrier_prod_share_constraint_rule**(*backend_model*, *group_name*, *what*)

Enforces shares of carrier_prod for groups of technologies and locations, on average over the entire model period. The share is relative to `supply` and `supply_plus` technologies only.

$$\sum_{loc::tech::carrier \in given\_group, timestep \in timesteps} carrier_{prod}(loc :: tech :: carrier, timestep) \leq share \times$$
$$loc::tech:carrier \in loc\_tech\_$$

calliope.backend.pyomo.constraints.group.**carrier_prod_share_per_timestep_constraint_rule**(*backend_model*, *group_name*, *timestep*, *what*)

Enforces shares of carrier_prod for groups of technologies and locations, in each timestep. The share is relative to `supply` and `supply_plus` technologies only.

$$\sum_{loc::tech::carrier \in given\_group} carrier_{prod}(loc :: tech :: carrier, timestep) \leq share \times \sum_{loc::tech:carrier \in loc\_tech\_carriers\_supply\_all \in}$$

calliope.backend.pyomo.constraints.group.**net_import_share_constraint_rule**(*backend_model*, *group_name*, *what*)

Enforces demand shares of net imports from transmission technologies for groups of locations, on average over the entire model period. Transmission within the group are ignored. The share is relative to demand technologies only.

$$\sum_{loc::tech::carrier \in loc\_tech\_carriers\_transmission \in given\_locations, timestep \in timesteps} carrier_{prod}(loc :: tech :: carrier, timestep) + l$$

calliope.backend.pyomo.constraints.group.**carrier_prod_constraint_rule**(*backend_model*, *group_name*, *what*)

Enforces carrier_prod for groups of technologies and locations, as a sum over the entire model period.

$$\sum_{loc::tech::carrier \in given\_group, timestep \in timesteps} carrier_{prod}(loc :: tech :: carrier, timestep) \leq carrier_prod_max$$

calliope.backend.pyomo.constraints.group.**carrier_con_constraint_rule**(*backend_model*, *constraint_group*, *what*)

Enforces carrier_con for groups of technologies and locations, as a sum over the entire model period. limits are always negative, so min/max is relative to zero (i.e. min = -1 means carrier_con must be -1 or less)

$$\sum_{loc::tech::carrier \in given\_group, timestep \in timesteps} carrier_{con}(loc :: tech :: carrier, timestep) \geq carrier_con_max$$

calliope.backend.pyomo.constraints.group.**energy_cap_share_constraint_rule**(*backend_model*, *constraint_group*, *what*)

Enforces shares of energy_cap for groups of technologies and locations. The share is relative to supply, supply_plus, conversion, and conversion_plus technologies only.

$$\sum_{loc::tech \in given\_group} energy_{cap}(loc :: tech) \leq share \times \sum_{loc::tech \in loc\_tech\_supply\_all \in given\_locations} energy_{cap}(loc :: tech)$$

calliope.backend.pyomo.constraints.group.**energy_cap_constraint_rule**(*backend_model*, *constraint_group*, *what*)

Enforce upper and lower bounds for energy_cap of energy_cap for groups of technologies and locations.

$$\sum_{loc::tech \in given\_group} energy_{cap}(loc :: tech) \leq energy\_cap\_max$$

$$\sum_{loc::tech \in given\_group} energy_{cap}(loc :: tech) \geq energy\_cap\_min$$

calliope.backend.pyomo.constraints.group.**storage_cap_constraint_rule**(*backend_model*, *constraint_group*, *what*)

Enforce upper and lower bounds of storage_cap for groups of technologies and locations.

$$\sum_{loc::tech \in given\_group} storage_{cap}(loc :: tech) \leq storage\_cap\_max$$

$$\sum_{loc::tech \in given\_group} storage_{cap}(loc :: tech) \geq storage\_cap\_min$$

calliope.backend.pyomo.constraints.group.**cost_cap_constraint_rule**(*backend_model*, *group_name*, *cost*, *what*)

Limit cost for a specific cost class to a certain value, i.e. -constrained costs, for groups of technologies and locations.

$$\sum loc :: tech \in loc\_techs_{group\_name}, timestep \in timesteps \boldsymbol{cost}(cost, loc :: tech, timestep) \left\{ \leq cost\_max(cost) \geq cost\_m \right.$$

calliope.backend.pyomo.constraints.group.**cost_investment_cap_constraint_rule**(*backend_model*, *group_name*, *cost*, *what*)

Limit investment costs specific to a cost class to a certain value, i.e. -constrained costs, for groups of technologies and locations.

$$\sum loc :: tech \in loc\_techs_{group\_name}, timestep \in timesteps \boldsymbol{cost\_investment}(cost, loc :: tech, timestep) \left\{ \leq cost\_inves \right.$$

calliope.backend.pyomo.constraints.group.**cost_var_cap_constraint_rule**(*backend_model*, *group_name*, *cost*, *what*)

Limit variable costs specific to a cost class to a certain value, i.e. -constrained costs, for groups of technologies and locations.

$$\sum loc :: tech \in loc\_techs_{group\_name}, timestep \in timesteps \boldsymbol{cost\_var}(cost, loc :: tech, timestep) \left\{ \leq cost\_var\_max(cost) \right.$$

calliope.backend.pyomo.constraints.group.**resource_area_constraint_rule**(*backend_model*, *constraint_group*, *what*)

Enforce upper and lower bounds of resource_area for groups of technologies and locations.

$$\boldsymbol{resource_{area}}(loc :: tech) \leq group\_resource\_area\_max$$

$$\boldsymbol{resource_{area}}(loc :: tech) \geq group\_resource\_area\_min$$

1.12 Development guide

Contributions are very welcome! See our contributors guide on GitHub for information on how to contribute.

The code lives on GitHub at calliope-project/calliope. Development takes place in the `master` branch. Stable versions are tagged off of `master` with semantic versioning.

Tests are included and can be run with `py.test` from the project's root directory.

Also see the list of open issues, planned milestones and projects for an overview of where development is heading, and join us on Gitter to ask questions or discuss code.

1.12.1 Installing a development version

As when installing a stable version, using `conda` is recommended.

To actively contribute to Calliope development, or simply track the latest development version, you'll instead want to clone our GitHub repository. This will provide you with the master branch in a known location on your local device.

First, clone the repository:

```
$ git clone https://github.com/calliope-project/calliope
```

Then install all development requirements for Calliope into a new environment, calling it e.g. `calliope_dev`:

```
$ conda env create -f requirements.yml -n calliope_dev
$ conda activate calliope_dev
```

Finally install Calliope itself as an editable installation with pip:

```
$ pip install -e calliope
```

Note: Most of our tests depend on having the CBC solver also installed, as we have found it to be more stable than GPLK. If you are running on a Unix system, then you can run `conda install coincbc` to also install the CBC solver. To install solvers other than CBC, and for Windows systems, see our *solver installation instructions*.

We use the code formatter black and before you contribute any code, you should ensure that you have run it through black. If you don't have a process for doing this already, you can install our configured pre-commit hook which will automatically run black on each commit:

```
$ pre-commit install
```

1.12.2 Creating modular extensions

As of version 0.6.0, dynamic loading of custom constraint generator extensions has been removed due it not not being used by users of Calliope. The ability to dynamically load custom functions to adjust time resolution remains (see below).

Time functions and masks

Custom functions that adjust time resolution can be loaded dynamically during model initialisation. By default, Calliope first checks whether the name of a function or time mask refers to a function from the `calliope.core.time.masks` or `calliope.core.time.funcs` module, and if not, attempts to load the function from an importable module:

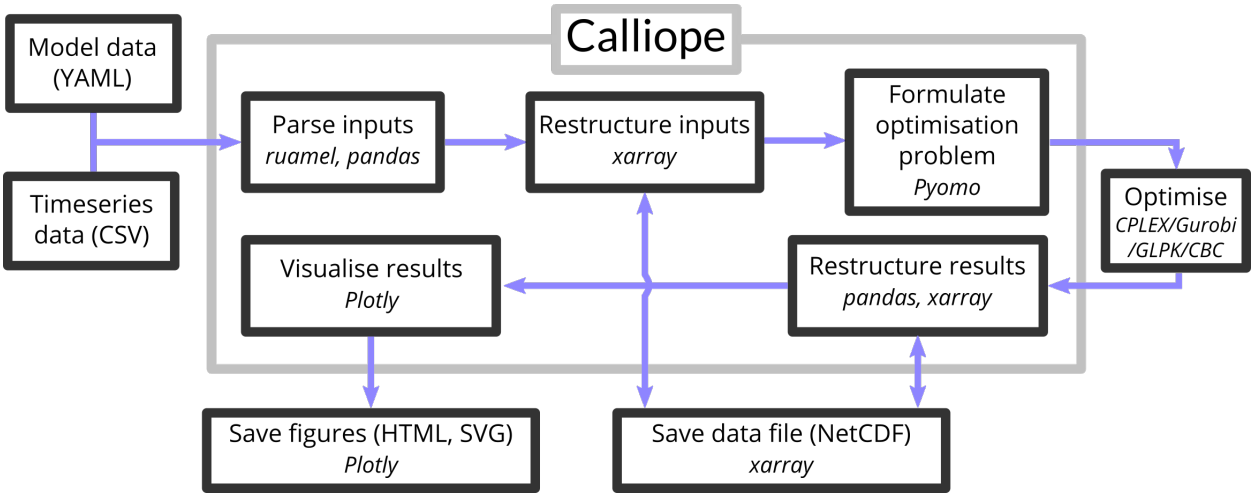
```
time:
   masks:
        - {function: week, options: {day_func: 'extreme', tech: 'wind', how: 'min'}}
        - {function: my_custom_module.my_custom_mask, options: {...}}
   function: my_custom_module.my_custom_function
   function_options: {...}
```

1.12.3 Understanding Calliope internal implementation

Worried about delving into the Calliope code? Confused by the structure? Fear not! The package is structured as best as possible to follow a clear workflow, which takes inputs on a journey from YAML and CSV files, via Pyomo objects, to a NetCDF file of results.

Overview

Calliope enables data stored in YAML and CSV files to be prepared for optimisation in a linear solver, and the results of optimisation to be analysed and/or saved. The internal workflow is shown below. The python packages ruamel.yaml and pandas are used to parse the YAML and CSV files, respectively. Xarray is then used to restructure the data into multidimensional arrays, ready for saving, plotting, or sending to the backend. The pyomo package is currently used in the backend to transform the xarray dataset into a pyomo ConcreteModel. All parameters, sets, constraints, and decision variables are defined as pyomo objects at this stage. Pyomo produces an LP file, which can be read in by the modeller's chosen solver. Results are extracted from pyomo into an xarray dataset, again ready to be analysed or saved.



Internal implementation

Taking a more detailed look at the workflow, a number of data objects are populated. On initialising a model, the *model_run* dictionary is created from the provided YAML and CSV files. Overrides (both from scenarios and location/link specific ones) are applied at this point. The *model_run* dictionary is then reformulated into multidimensional arrays of data and collated in the *model_data* xarray dataset. At this point, model initialisation has completed; model inputs can be accessed by the user, and edited if necessary.

On executing *model.run()*, only *model_data* is sent over to the backend, where the pyomo *ConcreteModel* is created and pyomo parameters (Param) and sets (Set) are populated using data from *model_data*. Decision variables (Var), constraints (Constraint), and the objective (Obj) are also initialised at this point. The model is then sent to the solver.

Upon solving the problem, the backend_model (pyomo ConcreteModel) is attached to the Model object and the results are added to *model_data*. Post-processing also occurs to clean up the results and to calculate certain indicators, such as the capacity factor of technologies. At this point, the model run has completed; model results can be accessed by the user, and saved or analysed as required.

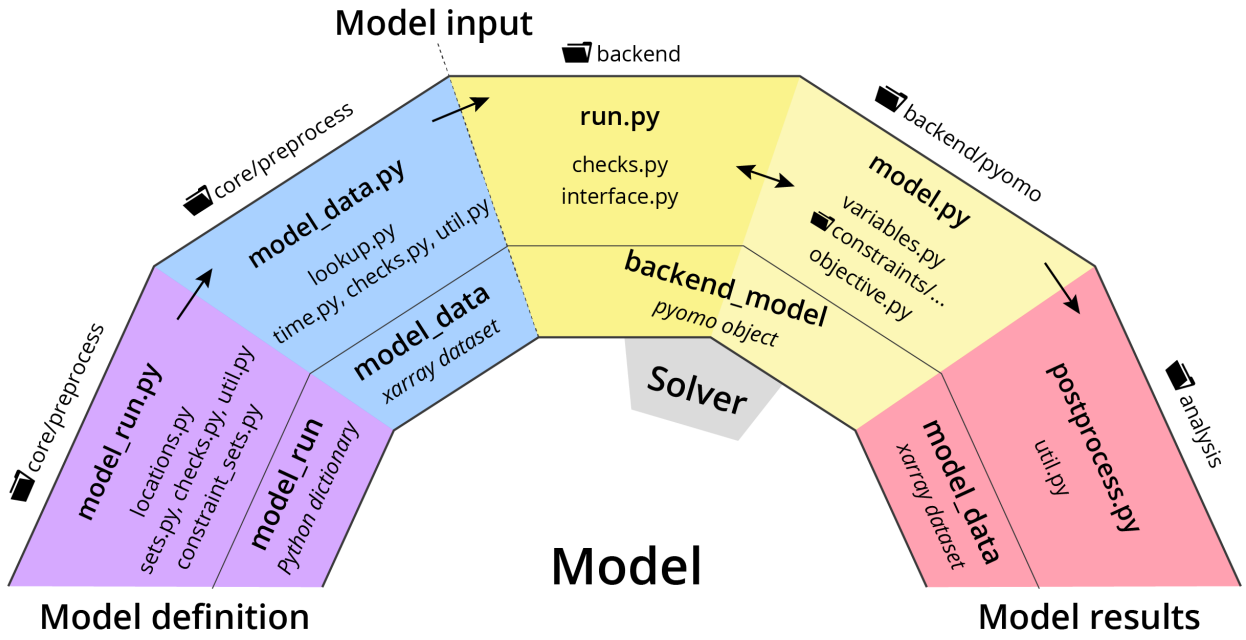


Fig. 16: Representation of Calliope internal implementation workflow. Five primary steps are shown, starting at the model definition and implemented clockwise. From inner edge to outer edge of the rainbow are: the data object produced by the step, primary and auxiliary python files in which functionality to produce the data object are found, and the folder containing the relevant python files for the step.

Exposing all methods and data attached to the Model object

The Model object begins as an empty class. Once called, it becomes an empty object which is populated with methods to access, analyse, and save the model data. The Model object is further augmented once *run* has been called, at which point, the backend model object can be accessed, directly or via a user-friendly interface. The notebook found here goes through each method and data object which can be accessed through the Model object. Most are hidden (using an underscore before the method name), as they aren't useful for the average user.

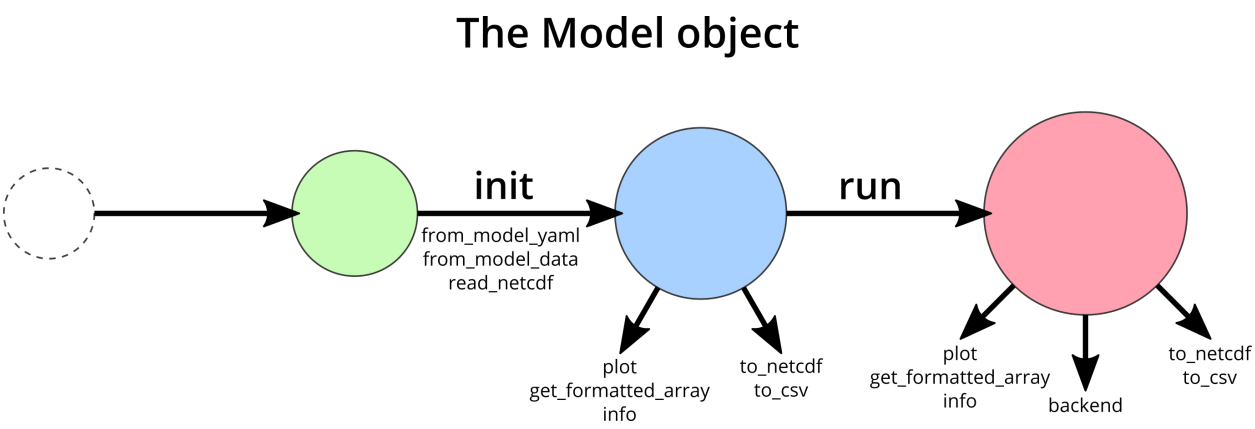


Fig. 17: Representation of the Calliope Model object, growing from an empty class to having methods to view, plot and save data, and to interface with the solver backend.

1.12.4 Contribution workflow

Have a bug fix or feature addition you'd like to see in the next stable release of Calliope? First, be sure to check out our list of open and closed issues to see whether this is something someone else has mentioned, or perhaps has even fixed. If it's there, you can add to the discussion, give it a thumbs up, or look to implement the change yourself. If it isn't there, then feel free to open your own issue, or you can head straight to implementing it. The below instructions are a more detailed description of our contribution guidelines, which you can refer to if you're already comfortable with using pytest and GitHub flows.

Implementing a change

When you want to change some part of Calliope, whether it is the software or the documentation, it's best to do it in a fork of the main Calliope project repository. You can find out more about how to fork a repository on GitHub's help pages. Your fork will be a duplicate of the Calliope master branch and can be 'cloned' to provide you with the repository on your own device

```
$ git clone https://github.com/your_username/calliope
```

If you want the local version of your fork to be in the same folder as your local version of the main Calliope repository, then you just need to specify a new directory name

```
$ git clone https://github.com/your_username/calliope your_new_directory_name
```

Following the instructions for *installing a development environment of Calliope*, you can create an environment specific to this installation of Calliope.

In making changes to your local version, it's a good idea to create a branch first, to not have your master branch diverge from that of the main Calliope repository

```
$ git branch new-fix-or-feature
```

Then, 'checkout' the branch so that the folder contents are specific to that branch

```
$ git checkout new-fix-or-feature
```

Finally, push the branch online, so it's existence is also in your remote fork of the Calliope repository (you'll find it in the dropdown list of branches at https://github.com/your_repository/calliope)

```
$ git push -u origin new-fix-or-feature
```

Now the files in your local directory can be edited with complete freedom. Once you have made the necessary changes, you'll need to test that they don't break anything. This can be done easily by changing to the directory into which you cloned your fork using the terminal / command line, and running pytest (make sure you have activated the conda environment and you have pytest installed: *conda install pytest*). Any change you make should also be covered by a test. Add it into the relevant test file, making sure the function starts with 'test_'. Since the whole test suite takes ~25 minutes to run, you can run specific tests, such as those you add in

```
$ pytest calliope/test/test_filename.py::ClassName::function_name
```

If tests are failing, you can debug them by using the pytest arguments `-x` (stop at the first failed test) and `--pdb` (enter into the debug console).

Once everything has been updated as you'd like (see the contribution checklist below for more on this), you can commit those changes. This stores all edited files in the directory, ready for pushing online

```
$ git add .
$ git checkout -m "Short message explaining what has been done in this commit."
```

If you only want a subset of edited files to go into this commit, you can specify them in the call to *git add*; the period adds all edited files.

If you're happy with your commit(s) then it is time to 'push' everything online using the command *git push*. If you're working with someone else on a branch and they have made changes, you can bring them into your local repository using the command *git pull*.

Now it is time to request that these changes are added into the main Calliope project repository! You can do this by starting a pull request. One of the core Calliope team will review the pull request and either accept it or request some changes before it's merged into the main Calliope repository. If any changes are requested, you can make those changes on your local branch, commit them, and push them online – your pull request will update automatically with those changes.

Once a pull request has been accepted, you can return your fork back to its master branch and sync it with the updated Calliope project master

```
$ git remote add upstream https://github.com/calliope-project/calliope
$ git fetch upstream master
$ git checkout master
$ git merge upstream/master
```

Contribution checklist

A contribution to the core Calliope code should meet the following requirements:

1. Test(s) added to cover contribution

   Tests ensure that a bug you've fixed will be caught in future, if an update to the code causes it to occur again. They also allow you to ensure that additional functionality works as you expect, and any change elsewhere in the code that causes it to act differently in future will be caught.

2. Documentation updated

   If you've added functionality, it should be mentioned in the documentation. You can find the reStructuredText (.rst) files for the documentation under 'doc/user'.

3. Changelog updated

   A brief description of the bug fixed or feature added should be placed in the changelog (changelog.rst). Depending on what the pull request introduces, the description should be prepended with *fixed*, *changed*, or *new*.

4. Coverage maintained or improved

   Coverage will be shown once all tests are complete online. It is the percentage of lines covered by at least one test. If you've added a test or two, you should be fine. But if coverage does go down it means that not all of your contribution has been tested!

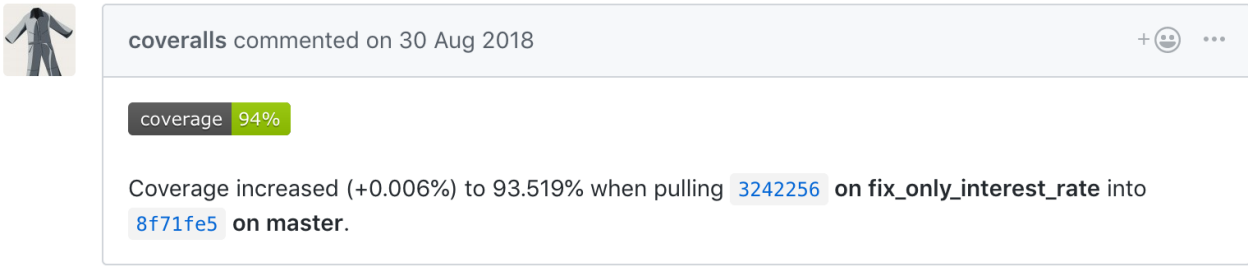


Fig. 18: Example of coverage notification in a pull request.

If you're not sure you've done everything to have a fully formed pull request, feel free to start it anyway. We can help guide you through making the necessary changes, once we have seen where you've got to.

1.12.5 Profiling

To profile a Calliope run with the built-in national-scale example model, then visualise the results with snakeviz:

```
make profile  # will dump profile output in the current directory
snakeviz calliope.profile  # launch snakeviz to visually examine profile
```

Use `mprof plot` to plot memory use.

Other options for visualising:

- Interactive visualisation with KCachegrind (on macOS, use QCachegrind, installed e.g. with `brew install qcachegrind`)

  ```
  pyprof2calltree -i calliope.profile -o calliope.calltree
  kcachegrind calliope.calltree
  ```

- Generate a call graph from the call tree via graphviz

  ```
  # brew install gprof2dot
  gprof2dot -f callgrind calliope.calltree | dot -Tsvg -o callgraph.svg
  ```

1.12.6 Checklist for new release

Pre-release

- Make sure all unit tests pass
- Build up-to-date Plotly plots for the documentation with (`make doc-plots`)
- Re-run tutorial Jupyter notebooks, found in *doc/_static/notebooks*
- Make sure documentation builds without errors
- Make sure the release notes are up-to-date, especially that new features and backward incompatible changes are clearly marked

Create release

- Change `_version.py` version number
- Update changelog with final version number and release date
- Commit with message "Release vXXXX", then add a "vXXXX" tag, push both to GitHub
- Create a release through the GitHub web interface, using the same tag, titling it "Release vXXXX" (required for Zenodo to pull it in)
- Upload new release to PyPI: `make all-dist`
- **Update the conda-forge package:**
  - **Fork conda-forge/calliope-feedstock, and update `recipe/meta.yaml` with:**
    - Version number: `{% set version = "XXXX" %}`
    - SHA256 of latest version from PyPI: `{% set sha256 = "XXXX" %}`
    - Reset `build: number: 0` if it is not already at zero
    - If necessary, carry over any changed requirements from `setup.py` or `requirements/base.yml`
  - Submit a pull request from an appropriately named branch in your fork (e.g. `vXXXX`) to the conda-forge/calliope-feedstock repository

Post-release

- Update changelog, adding a new vXXXX-dev heading, and update `_version.py` accordingly, in preparation for the next master commit
- Update the `calliope_version` setting in all example models to match the new version, but without the `-dev` string (so `0.6.0-dev` is `0.6.0` for the example models)

Note: Adding '-dev' to the version string, such as `__version__ = '0.1.0-dev'`, is required for the custom code in `doc/conf.py` to work when building in-development versions of the documentation.

CHAPTER

TWO

API DOCUMENTATION

Documents functions, classes and methods:

2.1 API Documentation

2.1.1 Model class

class calliope.**Model**(*config*, *model_data=None*, **args*, ***kwargs*)

A Calliope Model.

save_commented_model_yaml(*path*)

Save a fully built and commented version of the model to a YAML file at the given `path`. Comments in the file indicate where values were overridden. This is Calliope's internal representation of a model directly before the model_data xarray.Dataset is built, and can be useful for debugging possible issues in the model formulation.

run(*force_rerun=False*, ***kwargs*)

Run the model. If `force_rerun` is True, any existing results will be overwritten.

Additional kwargs are passed to the backend.

get_formatted_array(*var*, *index_format='index'*)

Return an xr.DataArray with locs, techs, and carriers as separate dimensions.

Parameters

var [str] Decision variable for which to return a DataArray.

index_format [str, default = 'index'] 'index' to return the *loc_tech(_carrier)* dimensions as individual indexes, 'multiindex' to return them as a MultiIndex. The latter has the benefit of having a smaller memory footprint, but you cannot undertake dimension specific operations (e.g. formatted_array.sum('locs'))

to_netcdf(*path*)

Save complete model data (inputs and, if available, results) to a NetCDF file at the given `path`.

to_csv(*path*, *dropna=True*)

Save complete model data (inputs and, if available, results) as a set of CSV files to the given `path`.

Parameters

dropna [bool, optional] If True (default), NaN values are dropped when saving, resulting in significantly smaller CSV files.

`to_lp`(*path*)
Save built model to LP format at the given `path`. If the backend model has not been built yet, it is built prior to saving.

2.1.2 Time series

`calliope.time.clustering.get_clusters`(*data*, *func*, *timesteps_per_day*, *tech=None*, *timesteps=None*, *k=None*, *variables=None*, ***kwargs*)
Run a clustering algorithm on the timeseries data supplied. All timeseries data is reshaped into one row per day before clustering into similar days.

Parameters

data [xarray.Dataset] Should be normalized

func [str] 'kmeans' or 'hierarchical' for KMeans or Agglomerative clustering, respectively

timesteps_per_day [int] Total number of timesteps in a day

tech [list, optional] list of strings referring to technologies by which clustering is undertaken. If none (default), all technologies within timeseries variables will be used.

timesteps [list or str, optional] Subset of the time domain within which to apply clustering.

k [int, optional] Number of clusters to create. If none (default), will use Hartigan's rule to infer a reasonable number of clusters.

variables [list, optional] data variables (e.g. *resource*, *energy_eff*) by whose values the data will be clustered. If none (default), all timeseries variables will be used.

kwargs [dict] Additional keyword arguments available depend on the *func*. For available KMeans kwargs see: http://scikit-learn.org/stable/modules/generated/sklearn.cluster.KMeans.html For available hierarchical kwargs see: http://scikit-learn.org/stable/modules/generated/sklearn.cluster.AgglomerativeClustering.html

Returns

——-

clusters [dataframe] Indexed by timesteps and with locations as columns, giving cluster membership for first timestep of each day.

clustered_data [sklearn.cluster object] Result of clustering using sklearn.KMeans(k).fit(X) or sklearn.KMeans(k).AgglomerativeClustering(X). Allows user to access specific attributes, for detailed statistical analysis.

`calliope.time.masks.extreme`(*data*, *tech*, *var='resource'*, *how='max'*, *length='1D'*, *n=1*, *groupby_length=None*, *padding=None*, *normalize=True*, ***kwargs*)
Returns timesteps for period of `length` where `var` for the technology `tech` across the given list of `locations` is either minimal or maximal.

Parameters

data [xarray.Dataset]

tech [str] Technology whose *var* to find extreme for.

var [str, optional] default 'resource'

how [str, optional] 'max' (default) or 'min'.

length [str, optional] Defaults to '1D'.

n [int, optional] Number of periods of *length* to look for, default is 1.

groupby_length [str, optional] Group time series and return *n* periods of *length* for each group.

padding [str, optional] Either Pandas frequency (e.g. '1D') or 'calendar_week'. If Pandas frequency, symmetric padding is undertaken, either side of *length* If 'calendar_week', padding is fit to the calendar week in which the extreme day(s) are found.

normalize [bool, optional] If True (default), data is normalized using `normalized_copy()`.

kwargs [dict, optional] Dimensions of the selected var over which to index. Any remaining dimensions will be flattened by mean

`calliope.time.masks.`**`extreme_diff`**(*data*, *tech0*, *tech1*, *var='resource'*, *how='max'*, *length='1D'*, *n=1*, *groupby_length=None*, *padding=None*, *normalize=True*, ***kwargs*)

Returns timesteps for period of `length` where the diffence in extreme value for `var` between technologies `tech0` and `tech1` is either a minimum or a maximum.

Parameters

data [xarray.Dataset]

tech0 [str] First technology for which we find the extreme of *var*

tech1 [str] Second technology for which we find the extreme of *var*

var [str, optional] default 'resource'

how [str, optional] 'max' (default) or 'min'.

length [str, optional] Defaults to '1D'.

n [int, optional] Number of periods of *length* to look for, default is 1.

groupby_length [str, optional] Group time series and return *n* periods of *length* for each group.

padding [str, optional] Either Pandas frequency (e.g. '1D') or 'calendar_week'. If Pandas frequency, symmetric padding is undertaken, either side of *length* If 'calendar_week', padding is fit to the calendar week in which the extreme day(s) are found.

normalize [bool, optional] If True (default), data is normalized using `normalized_copy()`.

kwargs [dict, optional] Dimensions of the selected var over which to index. Any remaining dimensions will be flattened by mean

`calliope.time.funcs.`**`resample`**(*data*, *timesteps*, *resolution*)

Function to resample timeseries data from the input resolution (e.g. 1H), to the given resolution (e.g. 2H)

Parameters

data [xarray.Dataset] calliope model data, containing only timeseries data variables

timesteps [str or list; optional] If given, apply resampling to a subset of the timeseries data

resolution [str] time resolution of the output data, given in Pandas time frequency format. E.g. 1H = 1 hour, 1W = 1 week, 1M = 1 month, 1T = 1 minute. Multiples allowed.

2.1.3 Analyzing models

class calliope.postprocess.plotting.plotting.**ModelPlotMethods**(*model*)

timeseries(***kwargs*)

Parameters

array [str or list; default = 'all'] options: 'all', 'results', 'inputs', the name/list of any energy carrier(s) (e.g. 'power'), the name/list of any input/output DataArray(s).

User can specify 'all' for all input/results timeseries plots, 'inputs' for just input timeseries, 'results' for just results timeseries, or the name of any data array to plot (in either inputs or results). In all but the last case, arrays can be picked from dropdown in visualisation. In the last case, output can be saved to SVG and a rangeslider can be used.

timesteps_zoom [int, optional] Number of timesteps to show initially on the x-axis (if not given, the full time range is shown by default).

rangeslider [bool, optional] If True, displays a range slider underneath the plot for navigating (helpful primarily in interactive use).

subset [dict, optional] Dictionary by which data is subset (uses xarray *loc* indexing). Keys any of ['timeseries', 'locs', 'techs', 'carriers', 'costs'].

sum_dims [str, optional] List of dimension names to sum plot variable over.

squeeze [bool, optional] Whether to squeeze out dimensions of length = 1.

html_only [bool, optional; default = False] Returns a html string for embedding the plot in a webpage

to_file [False or str, optional; default = False] Will save plot to file with the given name and extension. *to_file='plot.svg'* to save to SVG, *to_file='plot.png'* for a static PNG image. Allowed file extensions are: ['png', 'jpeg', 'svg', 'webp'].

layout_updates [dict, optional] The given dict will be merged with the Plotly layout dict generated by the Calliope plotting function, overwriting keys that already exist.

plotly_kwarg_updates [dict, optional] The given dict will be merged with the Plotly plot function's keyword arguments generated by the Calliope plotting function, overwriting keys that already exist.

capacity(***kwargs*)

Parameters

array [str or list; default = 'all'] options: 'all', 'results', 'inputs', the name/list of any energy capacity DataArray(s) from inputs/results. User can specify 'all' for all input/results capacities, 'inputs' for just input capacities, 'results' for just results capacities, or the name(s) of any data array(s) to plot (in either inputs or results). In all but the last case, arrays can be picked from dropdown in visualisation. In the last case, output can be saved to SVG.

orient [str, optional] 'h' for horizontal or 'v' for vertical barchart

subset [dict, optional] Dictionary by which data is selected (using xarray indexing *loc[]*). Keys any of ['timeseries', 'locs', 'techs', 'carriers', 'costs']).

sum_dims [str, optional] List of dimension names to sum plot variable over.

squeeze [bool, optional] Whether to squeeze out dimensions containing only single values.

html_only [bool, optional; default = False] Returns a html string for embedding the plot in a webpage

to_file [False or str, optional; default = False] Will save plot to file with the given name and extension. *to_file='plot.svg'* to save to SVG, *to_file='plot.png'* for a static PNG image. Allowed file extensions are: ['png', 'jpeg', 'svg', 'webp'].

layout_updates [dict, optional] The given dict will be merged with the Plotly layout dict generated by the Calliope plotting function, overwriting keys that already exist.

plotly_kwarg_updates [dict, optional] The given dict will be merged with the Plotly plot function's keyword arguments generated by the Calliope plotting function, overwriting keys that already exist.

`transmission`(***kwargs*)

Parameters

mapbox_access_token [str, optional] If given and a valid Mapbox API key, a Mapbox map is drawn for lat-lon coordinates, else (by default), a more simple built-in map.

html_only [bool, optional; default = False] Returns a html string for embedding the plot in a webpage

to_file [False or str, optional; default = False] Will save plot to file with the given name and extension. *to_file='plot.svg'* to save to SVG, *to_file='plot.png'* for a static PNG image. Allowed file extensions are: ['png', 'jpeg', 'svg', 'webp'].

layout_updates [dict, optional] The given dict will be merged with the Plotly layout dict generated by the Calliope plotting function, overwriting keys that already exist.

plotly_kwarg_updates [dict, optional] The given dict will be merged with the Plotly plot function's keyword arguments generated by the Calliope plotting function, overwriting keys that already exist.

`summary`(***kwargs*)

Plot a summary containing timeseries, installed capacities, and transmission plots. Returns a HTML string by default, returns None if `to_file` given (and saves the HTML string to file).

Parameters

to_file [str, optional] Path to output file to save HTML to.

mapbox_access_token [str, optional] (passed to plot_transmission) If given and a valid Mapbox API key, a Mapbox map is drawn for lat-lon coordinates, else (by default), a more simple built-in map.

2.1.4 Pyomo backend interface

`class calliope.backend.pyomo.interface.`**BackendInterfaceMethods**(*model*)

`access_model_inputs`()

If the user wishes to inspect the parameter values used as inputs in the backend model, they can access a new Dataset of all the backend model inputs, including defaults applied where the user did not specify anything for a loc::tech

`update_param`(**args*, ***kwargs*)

A Pyomo Param value can be updated without the user directly accessing the backend model.

Parameters

param [str] Name of the parameter to update

update_dict [dict] keys are parameter indeces (either strings or tuples of strings, depending on whether there is one or more than one dimension). Values are the new values being assigned to the parameter at the given indeces.

Returns

Value(s) will be updated in-place, requiring the user to run the model again to

see the effect on results.

`activate_constraint`(**args*, ***kwargs*)

Takes a constraint or objective name, finds it in the backend model and sets its status to either active or deactive.

Parameters

constraint [str] Name of the constraint/objective to activate/deactivate Built-in constraints include '_constraint'

active: bool, default=True status to set the constraint/objective

`rerun`(**args*, ***kwargs*)

Rerun the Pyomo backend, perhaps after updating a parameter value, (de)activating a constraint/objective or updating run options in the model model_data object (e.g. *run.solver*).

Returns

new_model [calliope.Model] New calliope model, including both inputs and results, but no backend interface.

2.1.5 Utility classes: AttrDict, Exceptions, Logging

`class calliope.core.attrdict.AttrDict`(*source_dict=None*)

A subclass of `dict` with key access by attributes:

```
d = AttrDict({'a': 1, 'b': 2})
d.a == 1  # True
```

Includes a range of additional methods to read and write to YAML, and to deal with nested keys.

`copy`()

Override copy method so that it returns an AttrDict

`init_from_dict`(*d*)

Initialize a new AttrDict from the given dict. Handles any nested dicts by turning them into AttrDicts too:

```
d = AttrDict({'a': 1, 'b': {'x': 1, 'y': 2}})
d.b.x == 1  # True
```

`classmethod from_yaml`(*f*, *resolve_imports=True*)

Returns an AttrDict initialized from the given path or file object `f`, which must point to a YAML file. The path can be a string or a pathlib.Path.

Parameters

f [str or pathlib.Path]

resolve_imports [bool or str, optional] If `resolve_imports` is True, top-level `import:` statements are resolved recursively. If `resolve_imports is False, top-level ``import:` statements are treated like any other key and not further processed. If `resolve_imports` is a string, such as `foobar`, import statements underneath that key are resolved, i.e. `foobar.import:`. When resolving import statements, anything defined locally overrides definitions in the imported file.

classmethod from_yaml_string(*string*, *resolve_imports=True*)
Returns an AttrDict initialized from the given string, which must be valid YAML.

set_key(*key*, *value*)
Set the given `key` to the given `value`. Handles nested keys, e.g.:

```
d = AttrDict()
d.set_key('foo.bar', 1)
d.foo.bar == 1  # True
```

get_key(*key*, *default=<calliope.core.attrdict.__Missing object>*)
Looks up the given `key`. Like set_key(), deals with nested keys.

If default is anything but `_MISSING`, the given default is returned if the key does not exist.

del_key(*key*)
Delete the given key. Properly deals with nested keys.

as_dict(*flat=False*)
Return the AttrDict as a pure dict (with nested dicts if necessary).

to_yaml(*path=None*)
Saves the AttrDict to the `path` as a YAML file, or returns a YAML string if `path` is None.

keys_nested(*subkeys_as='list'*)
Returns all keys in the AttrDict, sorted, including the keys of nested subdicts (which may be either regular dicts or AttrDicts).

If `subkeys_as='list'` (default), then a list of all keys is returned, in the form `['a', 'b.b1', 'b.b2']`.

If `subkeys_as='dict'`, a list containing keys and dicts of subkeys is returned, in the form `['a', {'b': ['b1', 'b2']}]`.

union(*other*, *allow_override=False*, *allow_replacement=False*, *allow_subdict_override_with_none=False*)
Merges the AttrDict in-place with the passed `other` AttrDict. Keys in `other` take precedence, and nested keys are properly handled.

If `allow_override` is False, a KeyError is raised if other tries to redefine an already defined key.

If `allow_replacement`, allow "_REPLACE_" key to replace an entire sub-dict.

If `allow_subdict_override_with_none` is False (default), a key of the form `this.that: None` in other will be ignored if subdicts exist in self like `this.that.foo: 1`, rather than wiping them.

exception calliope.exceptions.**ModelError**
ModelErrors should stop execution of the model, e.g. due to a problem with the model formulation or input data.

exception calliope.exceptions.**BackendError**

exception calliope.exceptions.**ModelWarning**
ModelWarnings should be raised for possible model errors, but where execution can still continue.

exception calliope.exceptions.**BackendWarning**

calliope.exceptions.**print_warnings_and_raise_errors**(*warnings=None*, *errors=None*)
Print warnings and raise ModelError from errors.

Parameters

warnings [list, optional]

errors [list, optional]

calliope.core.util.logging.**set_log_verbosity**(*verbosity='info'*, *include_solver_output=True*, *capture_warnings=True*)

Set the verbosity of logging and setup the root logger to log to console (stdout) with timestamp output formatting.

Parameters

verbosity [str, default 'info'] Logging level to display across all of Calliope. Can be one of 'debug', 'info', 'warning', 'error', or 'critical'.

include_solver_output [bool, default True] If True, the logging level for just the backend model is set to DEBUG, which turns on display of solver output.

capture_warnings [bool, default True] If True, also capture all warnings and log them to the WARNING level. This results in more consistent output when running interactively.

2.2 Index

CHAPTER

THREE

RELEASE HISTORY

3.1 Release History

3.1.1 0.6.8 (2022-02-07)

new run configuration parameter to enable relaxation of the *demand_share_per_timestep_decision* constraint.

new *storage_cap_min/equals/max* group constraints added.

changed Updated to Pyomo 6.2, pandas 1.3, xarray 0.20, numpy 1.20.

changed backwards-incompatible parameters defaulting to False now default to None, to avoid confusion with zero. To 'switch off' a constraint, a user should now set it to 'null' rather than 'false' in their YAML configuration.

changed *INFO* logging level includes logs for dataset cleaning steps before saving to NetCDF and for instantiation of timeseries clustering/resampling (if taking place).

fixed *demand_share_per_timestep_decision* constraint set includes all expected (location, technology, carrier) items. In the previous version, not all expected items were captured.

fixed Mixed dtype xarray dataset variables, where one dtype is boolean, are converted to float if possible. This overcomes an error whereby the NetCDF file cannot be created due to a mixed dtype variable.

3.1.2 0.6.7 (2021-06-29)

new *spores* run mode can skip the cost-optimal run, with the user providing initial conditions for *spores_score* and slack system cost.

new Support for Pyomo's *gurobi_persistent* solver interface, which enables a more memory- and time-efficient update and re-running of models. A new backend interface has been added to re-build constraints / the objective in the Gurobi persistent solver after updating Pyomo parameters.

new A scenario can now be a mix of overrides *and* other scenarios, not just overrides.

new *model.backend.rerun()* can work with both *spores* and *plan* run modes (previously only *plan* worked). In the *spores* case, this only works with a built backend that has not been previously run (i.e. *model.run(build_only=True)*), but allows a user to update constraints etc. before running the SPORES method.

changed backwards-incompatible Carrier-specific group constraints are only allowed in isolation (one constraint in the group).

changed If *ensure_feasibility* is set to *True*, *unmet_demand* will always be returned in the model results, even if the model is feasible. Fixes issue #355.

changed Updated to Pyomo 6.0, pandas 1.2, xarray 0.17.

changed Update CBC Windows binary link in documentation.

fixed AttrDict now has a *__name__* attribute, which makes pytest happy.

fixed CLI plotting command has been re-enabled. Fixes issue #341.

fixed Group constraints are more robust to variations in user inputs. This entails a trade-off whereby some previously accepted user configurations will no longer be possible, since we want to avoid the complexity of processing them.

fixed *demand_share_per_timestep_decision* now functions as expected, where it previously did not enforce the per-timestep share after having decided upon it.

fixed Various bugs squashed in running operate mode.

fixed Handle number of timesteps lower than the horizon length in *operate* mode (#337).

3.1.3 0.6.6 (2020-10-08)

new *spores* run mode now available, to find Spatially-explicit Practically Optimal REsultS (SPORES)

new New group constraints *carrier_con_min*, *carrier_con_max*, *carrier_con_equals* which restrict the total consumed energy of a subgroup of conversion and/or demand technologies.

new Add ability to pass timeseries as dataframes in *calliope.Model* instead of only as CSV files.

new Pyomo backend interfaces added to get names of all model objects (*get_all_model_attrs*) and to attach custom constraints to the backend model (*add_constraint*).

changed Parameters are assigned a domain in Pyomo based on their dtype in *model_data*

changed Internal code reorganisation.

changed Updated to Pyomo 5.7, pandas 1.1, and xarray 0.16

fixed One-way transmission technologies can have *om* costs

fixed Silent override of nested dicts when parsing YAML strings

3.1.4 0.6.5 (2020-01-14)

new New group constraints *energy_cap_equals*, *resource_area_equals*, and *energy_cap_share_equals* to add the equality constraint to existing *min/max* group constraints.

new New group constraints *carrier_prod_min*, *carrier_prod_max*, and *carrier_prod_equals* which restrict the absolute energy produced by a subgroup of technologies and locations.

new Introduced a *storage_discharge_depth* constraint, which allows to set a minimum stored-energy level to be preserved by a storage technology.

new New group constraints *net_import_share_min*, *net_import_share_max*, and *net_import_share_equals* which restrict the net imported energy of a certain carrier into subgroups of locations.

changed backwards-incompatible Group constraints with the prefix *supply_share* are renamed to use the prefix *carrier_prod_share*. This ensures consistent naming for all group constraints.

changed Allowed 'energy_cap_min' for transmission technologies.

changed Minor additions made to troubleshooting and development documentation.

changed backwards-incompatible The backend interface to update a parameter value (*Model.backend.update_param()*) has been updated to allow multiple values in a parameter to be updated at once, using a dictionary.

changed Allowed *om_con* cost for demand technologies. This is conceived to allow better representing generic international exports as demand sinks with a given revenue (e.g. the average electricity price on a given bidding zone), not restricted to any particular type of technology.

changed backwards-incompatible *model.backend.rerun()* returns a calliope Model object instead of an xarray Dataset, allowing a user to access calliope Model methods, such as *get_formatted_array*.

changed Carrier ratios can be loaded from file, to allow timeseries carrier ratios to be defined, e.g. `carrier_ratios.carrier_out_2.heat: file=ratios.csv`.

changed Objective function options turned into Pyomo parameters. This allows them to update through the *Model.backend.update_param()* functionality.

changed All model defaults have been moved to *defaults.yaml*, removing the need for *model.yaml*. A default location, link and group constraint have been added to *defaults.yaml* to validate input model keys.

changed backwards-incompatible Revised internal logging and warning structure. Less critical warnings during model checks are now logged directly to the INFO log level, which is displayed by default in the CLI, and can be enabled interactively by calling *calliope.set_log_verbosity()* without any options. The *calliope.set_log_level* function has been renamed to *calliope.set_log_verbosity* and includes the ability to easily turn on and off the display of solver output.

changed All group constraint values are parameters so they can be updated in the backend model

fixed Operate mode checks cleaned up to warn less frequently and to not be so aggressive at editing a users model to fit the operate mode requirements.

fixed Documentation distinctly renders inline Python, YAML, and shell code snippets.

fixed Tech groups are used to filter technologies to which group constraints can be applied. This ensures that transmission and storage technologies are included in cost and energy capacity group constraints. More comprehensive tests have been added accordingly.

fixed Models saved to NetCDF now include the fully built internal YAML model and debug data so that *Model.save_commented_model_yaml()* is available after loading a NetCDF model from disk

fixed Fix an issue preventing the deprecated *charge_rate* constraint from working in 0.6.4.

fixed Fix an issue that prevented 0.6.4 from loading NetCDF models saved with older versions of Calliope. It is still recommended to only load models with the same version of Calliope that they were saved with, as not all functionality will work when mixing versions.

fixed backwards-incompatible Updated to require pandas 0.25, xarray 0.14, and scikit-learn 0.22, and verified Python 3.8 compatibility. Because of a bugfix in scikit-learn 0.22, models using k-means clustering with a specified random seed may return different clusters from Calliope 0.6.5 on.

3.1.5 0.6.4 (2019-05-27)

new New model-wide constraint that can be applied to all, or a subset of, locations and technologies in a model, covering:

- *demand_share*, *supply_share*, *demand_share_per_timestep*, *supply_share_per_timestep*, each of which can specify *min*, *max*, and *equals*, as well as *energy_cap_share_min* and *energy_cap_share_max*. These supersede the *group_share* constraints, which are now deprecated and will be removed in v0.7.0.
- *demand_share_per_timestep_decision*, allowing the model to make decisions on the per-timestep shares of carrier demand met from different technologies.
- *cost_max*, *cost_min*, *cost_equals*, *cost_var_max*, *cost_var_min*, *cost_var_equals*, *cost_investment_max*, *cost_investment_min*, *cost_investment_equals*, which allow a user to constrain costs, including those not used in the objective.

- *energy_cap_min*, *energy_cap_max*, *resource_area_min*, *resource_area_max* which allow to constrain installed capacities of groups of technologies in specific locations.

new *asynchronous_prod_con* parameter added to the constraints, to allow a user to fix a storage or transmission technology to only be able to produce or consume energy in a given timestep. This ensures that unphysical dissipation of energy cannot occur in these technologies, by activating a binary variable (*prod_con_switch*) in the backend.

new Multi-objective optimisation problems can be defined by linear scalarisation of cost classes, using *run.objective_options.cost_class* (e.g. *{'monetary': 1, 'emissions': 0.1}*, which models an emissions price of 0.1 units of currency per unit of emissions)

new Storage capacity can be tied to energy capacity with a new *energy_cap_per_storage_cap_equals* constraint.

new The ratio of energy capacity and storage capacity can be constrained with a new *energy_cap_per_storage_cap_min* constraint.

new Easier way to save an LP file with a `--save_lp` command-line option and a `Model.to_lp` method

new Documentation has a new layout, better search, and is restructured with various content additions, such as a section on troubleshooting.

new Documentation for developers has been improved to include an overview of the internal package structure and a guide to contributing code via a pull request.

changed backwards-incompatible Scenarios in YAML files defined as list of override names, not comma-separated strings: *fusion_scenario: cold_fusion,high_cost* becomes *fusion_scenario: ['cold_fusion', 'high_cost']*. No change to the command-line interface.

changed *charge_rate* has been renamed to *energy_cap_per_storage_cap_max*. *charge_rate* will be removed in Calliope 0.7.0.

changed Default value of resource_area_max now is `inf` instead of `0`, deactivating the constraint by default.

changed Constraint files are auto-loaded in the pyomo backend and applied in the order set by 'ORDER' variables given in each constraint file (such that those constraints which depend on pyomo expressions existing are built after the expressions are built).

changed Error on defining a technology in both directions of the same link.

changed Any inexistent locations and / or technologies defined in model-wide (group) constraints will be caught and filtered out, raising a warning of their existence in the process.

changed Error on required column not existing in CSV is more explicit.

changed backwards-incompatible Exit code for infeasible problems now is 1 (no success). This is a breaking change when relying on the exit code.

changed *get_formatted_array* improved in both speed and memory consumption.

changed *model* and *run* configurations are now available as attributes of the Model object, specifically as editable dictionaries which automatically update a YAML string in the *model_data* xarray dataset attribute list (i.e. the information is stored when sending to the solver backend and when saving to and loading from NetCDF file)

changed All tests and example models have been updated to solve with Coin-CBC, instead of GLPK. Documentation has been updated to reflect this, and aid in installing CBC (which is not simple for Windows users).

changed Additional and improved pre-processing checks and errors for common model mistakes.

fixed Total levelised cost of energy considers all costs, but energy generation only from `supply`, `supply_plus`, `conversion`, and `conversion_plus`.

fixed If a space is left between two locations in a link (i.e. *A, B* instead of *A,B*), the space is stripped, instead of leading to the expectation of a location existing with the name ` B`.

fixed Timeseries efficiencies can be included in operate mode without failing on preprocessing checks.

fixed Name of data variables is retained when accessed through *model.get_formatted_array()*

fixed Systemwide constraints work in models without transmission systems.

fixed Updated documentation on amendments of abstract base technology groups.

fixed Models without time series data fail gracefully.

fixed Unknown technology parameters are detected and the user is warned.

fixed Loc::techs with empty cost classes (i.e. value == None) are handled by a warning and cost class deletion, instead of messy failure.

3.1.6 0.6.3 (2018-10-03)

new Addition of `flows` plotting function. This shows production and how much they exchange with other locations. It also provides a slider in order to see flows' evolution through time.

new `calliope generate_runs` in the command line interface can now produce scripts for remote clusters which require SLURM-based submission (`sbatch...`).

new backwards-incompatible Addition of `scenarios`, which complement and expand the existing `overrides` functionality. `overrides` becomes a top-level key in model configuration, instead of a separate file. The `calliope run` command has a new `--scenario` option which replaces –override_file, while `calliope generate_runs` has a new `--scenarios` option which replaces –override_file and takes a semicolon-separated list of scenario names or of group1,group2 combinations. To convert existing overrides to the new approach, simply group them under a top-level `overrides` key and import your existing overrides file from the main model configuration file with `import: ['your_overrides_file.yaml']`.

new Addition of `calliope generate_scenarios` command to allow automating the construction of scenarios which consist of many combinations of overrides.

new Added `--override_dict` option to `calliope run` and `calliope generate_runs` commands

new Added solver performance comparison in the docs. CPLEX & Gurobi are, as expected, the best options. If going open-source & free, CBC is much quicker than GLPK!

new Calliope is tested and confirmed to run on Python 3.7

changed *resource_unit* - available to *supply*, *supply_plus*, and *demand* technologies - can now be defined as 'energy_per_area', 'energy', or 'energy_per_cap'. 'power' has been removed. If 'energy_per_area' then available resource is the resource (CSV or static value) * resource_area, if 'energy_per_cap' it is resource * energy_cap. Default is 'energy', i.e. resource = available_resource.

changed Updated to xarray v0.10.8, including updates to timestep aggregation and NetCDF I/O to handle updated xarray functionality.

changed Removed `calliope convert` command. If you need to convert a 0.5.x model, first use `calliope convert` in Calliope 0.6.2 and then upgrade to 0.6.3 or higher.

changed Removed comment persistence in AttrDict and the associated API in order to improve compatibility with newer versions of ruamel.yaml

fixed Operate mode is more robust, by being explicit about timestep and loc_tech indexing in *storage_initial* preparation and *resource_cap* checks, respectively, instead of assuming an order.

fixed When setting *ensure_feasibility*, the resulting *unmet_demand* variable can also be negative, accounting for possible infeasibility when there is unused supply, once all demand has been met (assuming no load shedding abilities). This is particularly pertinent when the *force_resource* constraint is in place.

fixed When applying systemwide constraints to transmission technologies, they are no longer silently ignored. Instead, the constraint value is doubled (to account for the constant existence of a pair of technologies to describe one link) and applied to the relevant transmission techs.

fixed Permit groups in override files to specify imports of other YAML files

fixed If only *interest_rate* is defined within a cost class of a technology, the entire cost class is correctly removed after deleting the *interest_rate* key. This ensures an empty cost key doesn't break things later on. Fixes issue #113.

fixed If time clustering with 'storage_inter_cluster' = True, but no storage technologies, the model doesn't break. Fixes issue #142.

3.1.7 0.6.2 (2018-06-04)

new `units_max_systemwide` and `units_equals_systemwide` can be applied to an integer/binary constrained technology (capacity limited by `units` not `energy_cap`, or has an associated `purchase` (binary) cost). Constraint works similarly to existing `energy_cap_max_systemwide`, limiting the number of units of a technology that can be purchased across all locations in the model.

new backwards-incompatible `primary_carrier` for *conversion_plus* techs is now split into `primary_carrier_in` and `primary_carrier_out`. Previously, it only accounted for output costs, by separating it, *om_con* and *om_prod* are correctly accounted for. These are required conversion_plus essentials if there's more than one input and output carrier, respectively.

new Storage can be set to cyclic using `run.cyclic_storage`. The last timestep in the series will then be used as the 'previous day' conditions for the first timestep in the series. This also applies to `storage_inter_cluster`, if clustering. Defaults to False, with intention of defaulting to True in 0.6.3.

new On clustering timeseries into representative days, an additional set of decision variables and constraints is generated. This addition allows for tracking stored energy between clusters, by considering storage between every *datestep* of the original (unclustered) timeseries as well as storage variation within a cluster.

new CLI now uses the IPython debugger rather than built-in `pdb`, which provides highlighting, tab completion, and other UI improvements

new AttrDict now persists comments when reading from and writing to YAML files, and gains an API to view, add and remove comments on keys

fixed Fix CLI error when running a model without transmission technologies

fixed Allow plotting for inputs-only models, single location models, and models without location coordinates

fixed Fixed negative `om_con` costs in conversion and conversion_plus technologies

3.1.8 0.6.1 (2018-05-04)

new Addition of user-defined datestep clustering, accessed by *clustering_func:file=filename.csv:column* in time aggregation config

new Added `layout_updates` and `plotly_kwarg_updates` parameters to plotting functions to override the generated Plotly configuration and layout

changed Cost class and sense (maximize/minimize) for objective function may now be specified in run configuration (default remains monetary cost minimization)

changed Cleaned up and documented `Model.save_commented_model_yaml()` method

fixed Fixed error when calling `--save_plots` in CLI

fixed Minor improvements to warnings

fixed Pure dicts can be used to create a `Model` instance

fixed `AttrDict.union` failed on all-empty nested dicts

3.1.9 0.6.0 (2018-04-20)

Version 0.6.0 is an almost complete rewrite of most of Calliope's internals. See user/whatsnew_060 for a more detailed description of the many changes.

Major changes

changed backwards-incompatible Substantial changes to model configuration format, including more verbose names for most settings, and removal of run configuration files.

new backwards-incompatible Complete rewrite of Pyomo backend, including new various new and improved functionality to interact with a built model (see user/whatsnew_060).

new Addition of a `calliope convert` CLI tool to convert 0.5.x models to 0.6.0.

new Experimental ability to link to non-Pyomo backends.

new New constraints: `resource_min_use` constraint for `supply` and `supply_plus` techs.

changed backwards-incompatible Removal of settings and constraints includes `subset_x`, `subset_y`, `s_time`, `r2`, `r_scale_to_peak`, `weight`.

changed backwards-incompatible `system_margin` constraint replaced with `reserve_margin` constraint.

changed backwards-incompatible Removed the ability to load additional custom constraints or objectives.

3.1.10 0.5.5 (2018-02-28)

- fixed Allow *r_area* to be non-zero if either of *e_cap.max* or *e_cap.equals* is set, not just *e_cap.max*.
- fixed Ensure static parameters in resampled timeseries are caught in constraint generation
- fixed Fix time masking when set_t.csv contains sub-hourly resolutions

3.1.11 0.5.4 (2017-11-10)

Major changes

- fixed *r_area_per_e_cap* and *r_cap_equals_e_cap* constraints have been separated from r_area and r_cap constraints to ensure that user specified *r_area.max* and *r_cap.max* constraints are observed.
- changed technologies and location subsets are now communicated with the solver as a combined location:technology subset, to reduce the problem size, by ignoring technologies at locations in which they have not been allowed. This has shown drastic improvements in Pyomo preprocessing time and memory consumption for certain models.

Other changes

- fixed Allow plotting carrier production using *calliope.analysis.plot_carrier_production* if that carrier does not have an associated demand technology (previously would raise an exception).
- fixed Define time clustering method (sum/mean) for more constraints that can be time varying. Previously only included *r* and *e_eff*.
- changed storage technologies default *s_cap.max* to *inf*, not 0 and are automatically included in the *loc_tech_store* subset. This ensures relevant constraints are not ignored by storage technologies.
- changed Some values in the urban scale MILP example were updated to provide results that would show the functionality more clearly
- changed technologies have set colours in the urban scale example model, as random colours were often hideous.
- changed ruamel.yaml, not ruamel_yaml, is now used for parsing YAML files.
- fixed e_cap constraints for unmet_demand technologies are ignored in operational mode. Capacities are fixed for all other technologies, which previously raised an exception, as a fixed infinite capacity is not physically allowable.
- fixed stack_weights were strings rather than numeric datatypes on reading NetCDF solution files.

3.1.12 0.5.3 (2017-08-22)

Major changes

- new (BETA) Mixed integer linear programming (MILP) capabilities, when using `purchase` cost and/or `units.max/min/equals` constraints. Integer/Binary decision variables will be applied to the relevant technology-location sets, avoiding unnecessary complexity by describing all technologies with these decision variables.

Other changes

- changed YAML parser is now ruamel_yaml, not pyyaml. This allows scientific notation of numbers in YAML files (#57)
- fixed Description of PV technology in urban scale example model now more realistic
- fixed Optional ramping constraint no longer uses backward-incompatible definitions (#55)
- fixed One-way transmission no longer forces unidirectionality in the wrong direction
- fixed Edge case timeseries resource combinations, where infinite resource sneaks into an incompatible constraint, are now flagged with a warning and ignored in that constraint (#61)
- fixed e_cap.equals: 0 sets a technology to a capacity of zero, instead of ignoring the constraint (#63)
- fixed depreciation_getter now changes with location overrides, instead of just checking the technology level constraints (#64)
- fixed Time clustering now functions in models with time-varying costs (#66)
- changed Solution now includes time-varying costs (costs_variable)
- fixed Saving to NetCDF does not affect in-memory solution (#62)

3.1.13 0.5.2 (2017-06-16)

- changed Calliope now uses Python 3.6 by default. From Calliope 0.6.0 on, Python 3.6 will likely become the minimum required version.
- fixed Fixed a bug in distance calculation if both lat/lon metadata and distances for links were specified.
- fixed Fixed a bug in storage constraints when both `s_cap` and `e_cap` were constrained but no `c_rate` was given.
- fixed Fixed a bug in the system margin constraint.

3.1.14 0.5.1 (2017-06-14)

new backwards-incompatible Better coordinate definitions in metadata. Location coordinates are now specified by a dictionary with either lat/lon (for geographic coordinates) or x/y (for generic Cartesian coordinates), e.g. `{lat: 40, lon: -2}` or `{x: 0, y: 1}`. For geographic coordinates, the `map_boundary` definition for plotting was also updated in accordance. See the built-in example models for details.

new Unidirectional transmission links are now possible. See the documentation on transmission links.

Other changes

- fixed Missing urban-scale example model files are now included in the distribution
- fixed Edge cases in `conversion_plus` constraints addressed
- changed Documentation improvements

3.1.15 0.5.0 (2017-05-04)

Major changes

new Urban-scale example model, major revisions to the documentation to accommodate it, and a new `calliope.examples` module to hold multiple example models. In addition, the `calliope new` command now accepts a `--template` option to select a template other than the default national-scale example model, e.g.: `calliope new my_urban_model --template=UrbanScale`.

new Allow technologies to generate revenue (by specifying negative costs)

new Allow technologies to export their carrier directly to outside the system boundary

new Allow storage & supply_plus technologies to define a charge rate (c_rate), linking storage capacity (s_cap) with charge/discharge capacity (e_cap) by s_cap * c_rate => e_cap. As such, either s_cap.max & c_rate or e_cap.max & c_rate can be defined for a technology. The smallest of *s_cap.max * c_rate* and *e_cap.max* will be taken if all three are defined.

changed backwards-incompatible Revised technology definitions and internal definition of sets and subsets, in particular subsets of various technology types. Supply technologies are now split into two types: `supply` and `supply_plus`. Most of the more advanced functionality of the original `supply` technology is now contained in `supply_plus`, making it necessary to update model definitions accordingly. In addition to the existing `conversion` technology type, a new more complex `conversion_plus` was added.

Other changes

- changed backwards-incompatible Creating a `Model()` with no arguments now raises a `ModelError` rather than returning an instance of the built-in national-scale example model. Use the new `calliope.examples` module to access example models.
- changed Improvements to the national-scale example model and its tutorial notebook
- changed Removed SolutionModel class
- fixed Other minor fixes

3.1.16 0.4.1 (2017-01-12)

- new Allow profiling with the `--profile` and `--profile_filename` command-line options
- new Permit setting random seed with `random_seed` in the run configuration
- changed Updated installation documentation using conda-forge package
- fixed Other minor fixes

3.1.17 0.4.0 (2016-12-09)

Major changes

new Added new methods to deal with time resolution: clustering, resampling, and heuristic timestep selection

changed backwards-incompatible Major change to solution data structure. Model solution is now returned as a single xarray DataSet instead of multiple pandas DataFrames and Panels. Instead of as a generic HDF5 file, complete solutions can be saved as a NetCDF4 file via xarray's NetCDF functionality.

While the recommended way to save and process model results is by NetCDF4, CSV saving functionality has now been upgraded for more flexibility. Each variable is saved as a separate CSV file with a single value column and as many index columns as required.

changed backwards-incompatible Model data structures simplified and based on xarray

Other changes

- new Functionality to post-process parallel runs into aggregated NetCDF files in `calliope.read`
- changed Pandas 0.18/0.19 compatibility
- changed 1.11 is now the minimum required numpy version. This version makes datetime64 tz-naive by default, thus preventing some odd behavior when displaying time series.
- changed Improved logging, status messages, and error reporting
- fixed Other minor fixes

3.1.18 0.3.7 (2016-03-10)

Major changes

changed Per-location configuration overrides improved. All technology constraints can now be set on a per-location basis, as can costs. This applies to the following settings:

- `techname.x_map`
- `techname.constraints.*`
- `techname.constraints_per_distance.*`
- `techname.costs.*`

The following settings cannot be overridden on a per-location basis:

- Any other options directly under `techname`, such as `techname.parent` or `techname.carrier`
- `techname.costs_per_distance.*`
- `techname.depreciation.*`

Other changes

- fixed Improved installation instructions
- fixed Pyomo 4.2 API compatibility
- fixed Other minor fixes

3.1.19 0.3.6 (2015-09-23)

- fixed Version 0.3.5 changes were not reflected in tutorial

3.1.20 0.3.5 (2015-09-18)

Major changes

new New constraint to constrain total (model-wide) installed capacity of a technology (`e_cap.total_max`), in addition to its per-node capacity (`e_cap.max`)

changed Removed the `level` option for locations. Level is now implicitly derived from the nested structure given by the `within` settings. Locations that define no or an empty `within` are implicitly at the topmost (0) level.

changed backwards-incompatible Revised configuration of capacity constraints: `e_cap_max` becomes `e_cap.max`, addition of `e_cap.min` and `e_cap.equals` (analogous for r_cap, s_cap, rb_cap, r_area). The `e_cap.equals` constraint supersedes `e_cap_max_force` (analogous for the other constraints). No backwards-compatibility is retained, models must change all constraints to the new formulation. See *Per-tech constraints* for a complete list of all available constraints. Some additional constraints have name changes:

- `e_cap_max_scale` becomes `e_cap_scale`
- `rb_cap_follows` becomes `rb_cap_follow`, and addition of `rb_cap_follow_mode`
- `s_time_max` becomes `s_time.max`

changed backwards-incompatible All optional constraints are now grouped together, under `constraints.optional`:

- `constraints.group_fraction.group_fraction` becomes `constraints.optional.group_fraction`

- `constraints.ramping.ramping_rate` becomes `constraints.optional.ramping_rate`

Other changes

- new analysis.map_results function to extract solution details from multiple parallel runs
- new Various other additions to analysis functionality, particularly in the analysis_utils module
- new analysis.get_levelized_cost to get technology and location specific costs
- new Allow dynamically loading time mask functions
- changed Improved summary table in the model solution: now shows only aggregate information for transmission technologies, also added missing `s_cap` column and technology type
- fixed Bug causing some total levelized transmission costs to be infinite instead of zero
- fixed Bug causing some CSV solution files to be empty

3.1.21 0.3.4 (2015-04-27)

- fixed Bug in construction and fixed O&M cost calculations in operational mode

3.1.22 0.3.3 (2015-04-03)

Major changes

changed In preparation for future enhancements, the ordering of location levels is flipped. The top-level locations at which balancing takes place is now level 0, and may contain level 1 locations. This is a backwards-incompatible change.

changed backwards-incompatible Refactored time resolution adjustment functionality. Can now give a list of masks in the run configuration which will all be applied, via `time.masks`, with a base resolution via `time.resolution` (or instead, as before, load a resolution series from file via `time.file`). Renamed the `time_functions` submodule to `time_masks`.

Other changes

- new Models and runs can have a `name`
- changed More verbose `calliope run`
- changed Analysis tools restructured
- changed Renamed `debug.keepfiles` setting to `debug.keep_temp_files` and better documented debug configuration

3.1.23 0.3.2 (2015-02-13)

- new Run setting `model_override` allows specifying the path to a YAML file with overrides for the model configuration, applied at model initialization (path is given relative to the run configuration file used). This is in addition to the existing `override` setting, and is applied first (so `override` can override `model_override`).
- new Run settings `output.save_constraints` and `output.save_constraints_options`
- new Run setting `parallel.post_run`
- changed Solution column names more in line with model component names
- changed Can specify more than one output format as a list, e.g. `output.format: ['csv', 'hdf']`
- changed Run setting `parallel.additional_lines` renamed to `parallel.pre_run`
- changed Better error messages and CLI error handling
- fixed Bug on saving YAML files with numpy dtypes fixed
- Other minor improvements and fixes

3.1.24 0.3.1 (2015-01-06)

- Fixes to time_functions
- Other minor improvements and fixes

3.1.25 0.3.0 (2014-12-12)

- Python 3 and Pyomo 4 are now minimum requirements
- Significantly improved documentation
- Improved model solution management by saving to HDF5 instead of CSV
- Calculate shares of technologies, including the ability to define groups for the purpose of computing shares
- Improved operational mode
- Simplified time_tools
- Improved output plotting, including dispatch, transmission flows, and installed capacities, and added model configuration to support these plots
- `r` can be specified as power or energy
- Improved solution speed
- Better error messages and basic logging
- Better sanity checking and error messages for common mistakes
- Basic distance-dependent constraints (only implemented for e_loss and cost of e_cap for now)
- Other improvements and fixes

3.1.26 0.2.0 (2014-03-18)

- Added cost classes with a new set `k`
- Added energy carriers with a new set `c`
- Added conversion technologies
- Speed improvements and simplifications
- Ability to arbitrarily nest model configuration files with `import` statements
- Added additional constraints
- Improved configuration handling
- Ability to define timestep options in run configuration
- Cleared up terminology (nodes vs locations)
- Improved TimeSummarizer masking and added new masks
- Removed technology classes
- Improved operational mode with results output matching planning mode and dynamic updating of parameters in model instance
- Working parallel_tools
- Improved documentation
- Apache 2.0 licensed
- Other improvements and fixes

3.1.27 0.1.0 (2013-12-10)

- Some semblance of documentation
- Usable built-in example model
- Improved and working TimeSummarizer
- More flexible masking for TimeSummarizer
- Ability to add additional constraints without editing core source code
- Some basic test coverage
- Working parallel run configuration system

Release history

CHAPTER

FOUR

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