ficus Documentation

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Contents

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CHAPTER 1

Contents

This documentation contains the following pages:

1.1 Overview

ficus consists of several **model entities**. These are external imported/exported commodities, processes and storages. Demand and intermittent commodity supply are modelled through time-series datasets.

The objective of the model is to supply the given demand with minimal costs. The main restriction is the power balance of every commodity for every time-step. Commodities are goods that can be imported/exported, generated, stored and consumed. They are represented by their power flow (in kW) per time-step.

The timebase of the model can be configured depending on the timebase of the given data (demand). For all commodities and entities then the same timebase is used.

Note: All resulting costs of the optimisation are **annualized**.

1.1.1 External imported/exported commodities

External imported/exported commodities are goods that can be imported or exported from/to "external sources", e.g. the electric grid. The prices for buying/selling for every time-step are given by a time-series.

Additional a demand rate with an extra time interval can be given, to consider peak demand charges. A `Demand-Rate-Factor` time-series allows to raise, reduce or turn off the demand rate for specific time-steps to consider special tariff systems.

External imported/exported commodities are defined over the commodity itself `(commodity)`, for example `(elec)` or `(heat)`.

1.1.2 Process

Processes describe conversion technologies from one commodity to another. They can be visualised like a black box with multiple inputs (commodities) and multiple outputs (commodities). Conversion efficiencies between inputs and outputs for full load (and optional part-load) are the main technical parameter. Fixed costs for investment and maintenance (per capacity) and variable costs for operation (per output) are the economic parameters.

Processes can be assigned to a `Process Class`, which allows to consider additional fees/subsidies for inputs or outputs of this class (e.g. subsidies for pv generation).

Processes are defined over the tuple `(process , number, commodity, direction)` that specifies the inputs and outputs for that process. The `number` variable is needed, if more than one identical process is given For example, `(chp, 1, gas, In)`, `(chp, 1, electricity, Out)` and `(chp, 1, heat, Out)` describes that the process named `chp` (combined heat and power) has a single input `gas` and two outputs `electricity` and `heat`.

1.1.3 Storage

Storage describes the possibility to deposit a deliberate amount of energy in form of one commodity at one time step, and later retrieving it. Efficiencies for charging/discharging and self discharge depict losses during input/output. Storage is characterised by capacities both for energy content (in kWh) and charge/discharge power (in kW). Both capacities have independent sets of investment, fixed and variable cost parameters to allow for a very flexible parametrization of various storage technologies from batteries to hot water tanks.

Storage is defined over the tuple `(storage, number, stored commodity)`. For example, `(Li-Ion Battery, 1, electricity)` represents a Li-Ion Battery that can store and retrieve energy in form of electricity.

1.1.4 Timeseries

Demand

Each commodity `(demand commodity)` may have one time-series, describing the (average) power demand (kW) per time-step. They are a crucial input parameter, as the whole optimisation aims to satisfy these demands with minimal costs from the given technologies (process, storage, external import/export).

Intermittent Supply

A time-series normalised to a maximum value of 1 relative to the installed capacity of a process using this commodity as input. For example, a wind power time-series should reach value 1, when the wind speed exceeds the modelled wind turbine's design wind speed is exceeded. This implies that any non-linear behaviour of intermittent processes can already be incorporated while preparing this time-series.

1.2 Run ficus

1.2.1 Run from Python

Running the model from python gives you more options for running the optimisation and plotting the results. Simply run the `runficus.py` script in the `examples` folder using e.g. python, ipython or spyder. After running the script, the shell should show the actual status and a few minutes later six result figures should show up. The sub-folder `result` should contain the saved result figures as well as a result-file.

runficus.py

Here the `runficus.py` script is explained step by step, so you can change it and use it for your own model.

```
import os
import ficus
```

Two packages are included.

- os is a builtin Python module, included here for its os.path submodule that offers operating system independent path manipulation routines.
- ficus is the module whose functions are used mainly in this script. These are `prepare_result_directory()`, `run_ficus()`, `report()` and `result_figures()`.

To import ficus, `ficus.py` hast to be either in the same directory than `runficus.py` or in any directory, that is searched by python. To make sure this is the case, follow step 4 of the :ref:‘ installation <install-ref>‘.

```
input_file = 'example.xlsx'
```

Gives the path to the `input_file` used for model creation. If the file is not in the same folder than `ficus.py`, give the FULL PATH (e.g. C:\YOUR\INPUT\FILE.xlsx). To run one of the other examples, just change the name of the input file.

```
result_folder = 'result'
result_name = os.path.splitext(os.path.split(input_file)[1])[0]
result_dir = ficus.prepare_result_directory(result_folder,result_name)
```

Creates a time stamped folder `result_name-TIME` within the `result_folder` directory and saves the full path to `result_dir`. Give FULL PATH for `result_folder`, if it should not be in the same directory, than `runficus.py`

```
prob = ficus.run_ficus(input_file, opt = 'cbc', neos=True)
```

The `run_ficus()` function, is the "work horse", where most computation and time is spent. The optimization problem is first defined and filled with values from the `input_file`. Then the solver `opt` is called to solve the model. If `neos` is set to `True`, the problem is sent to the 'NEOS Server for Optimization'_ to solve the problem (Note, that using some solvers on NEOS require a license). If `neos` is set to false, the locally installed solver is used (if installed). After solving the problem the results are read back to the `prob` object.

If locally installed solver gurobi or cplex are used, the parameter `Threads` allows to set the maximal number of simultaneous CPU threads.

```
ficus.report(prob, result_dir)
```

Saves the results from the object `prob` to an excel file in the directory `result_dir`.

```
ficus.result_figures(result_dir,prob=prob, show=True)
```

Reads and plots the results from the object `prob` and saves them in the directory `result_dir`. Can also be used to plot data from a given result-file with the Parameter `resultfile=PATH\\TO\\RESULTFILE.xlsx` instead of giving `prob`. `show` turns on/off showing the plots.

1.2.2 Run from Excel

For an easy first run of ficus without using any python environment a small macro in VBA allows running the optimization directly from Excel. Still python an all needed packages have to be installed on the computer.

- Open the file `example_fromexcel.xlsm` in the `examples` folder
- Go to the `RUN` sheet and choose a solver. If you choose any other than a `neos-...` solver, the solver hast to be installed locally on your computer. With me only the `mosek` and the `cbc` solver from NEOS Server for Optimization are working (no installation of solvers required)
- Push the `RUN OPTIMIZATION` button.

A cmd window should appear showing the actual status and a few minutes later six result figures should show up. The sub-folder `result` should contain the saved result figures as well as a result-file.

Using this way of running the model, the function `run_from_excel()` from the `ficus.py` script is called within VBA. This requires, that `ficus.py` can be found by python. To make sure this is the case, follow step 4 of the *installation*.

1.3 Tutorial

This tutorial describes how to create the data input and run your own model based on an example.

1.3.1 Create Input File

The following tutorial is a step by step explanation of how to create your own input file.

For the sake of an example, assume you want to build a new factory named *NewFactory* and cover its energy demand cost optimal. You have the (predicted) demand time-series in 15 minute time resolution for electricity (`elec`) and heat (`heat`) for 7 days (672 time-steps). You can import electricity and gas through the given infrastructure and export electricity back to the grid. You consider following processes/storages for converting/storing energy:

- A combined heat and power plant (`chp`) to convert gas to electricity and heat, limited to 1,000,000 kW
- Two different wind turbines (`wind_1` and `wind_2`), limited to 20,000 kW total

- A gas boiler (`boiler`) to convert gas to heat, limited to 1,000,000 kW
- A heat storages (`heat_storage`) to store heat, limited to 30,000 kWh
- A battery storage (`battery`) to store electricity, limited to 100,000 kWh

First make a copy of `example.xlsx` or `example_fromexcel.xlsm` (`example` folder) depending on how you want to run the model and give it the name `NewFactory.xlsx` or `NewFactory.xlsm`. Now edit the new file step by step following the instructions.

Time-Settings

Set timebase of time dependent Data and time-steps to be optimized

- **timebase**: time-interval between time-steps of all given time-series data.
- **start**: First time-step to use for the optimisation
- **end**: Last time-step to use for the optimisation

Edit Example: Keep the timebase at 900s (=15 minutes), the start time-step at 1 and the end time-step at 672 (optimise the whole 7 days)

Table 1.1: Sheet **Time-Settings**;

Info	timebase	start	end
Time	900	1	672

MIP-Equations

Activate/deactivate specific equations. If all settings are set to `no`, the problem will be a linear optimisation problem without integer variables. This will result and less computation time for solving of the problem. Activating one/more of the settings will activate equations, that allow additional restriction but may lead to longer claculation of the model because integer variable have to be used. The problem will then become a mixed integer linear optimisation problem.

- **Storage In-Out**: Prevents storages from charging and discharging one commodity at the same time, if activated. This can happen, when dumping energy of one commodity will lead to lower total costs. The model then uses the efficiency of the storage to dump the energy with no dumping costs.
- **Partload**: Consider minimum part-load settings, part-load efficiencies as well as start-up costs of processes.
- **Min-Cap**: Consider minimal installed capacities of processes and storages. This allows to set a minimum capacity of processes and storages, that has to be build, if the process is built at all (it still can not be built at all). Setting minimal and maximal capacities of processes/storages to the same level, this allows investigating if building a specific process/storage with a specific size is cost efficient.

See *MIP-Equations* for a more detailed description on the effects of activating one of the equations with examples.

Edit Example: Keep all settings deactivated.

Table 1.2: Sheet **MIP-Equations**

Equation	Active
Storage In-Out	no
Partload	no
Min-Cap	no

Ext-Commodities

List of all commodities than can be imported/exported. Set demand charge, time interval for demand charge, import/export limits and minimum operating hours.

For every commodity that can be imported/exported:

- **demand rate**: demand rate (in Euro/kW/a) to calculate the 'peak demand charge'_ of one commodity. The highest imported power during a specific time period (`time-interval-demand-rate`) of highest use in the year is used to calculate the demand charges by multiplication with the demand rate
- **time-interval-demand-rate**: time period or time interval used to determine the highest imported power use in the year for calculating the peak demnd charge
- **p-max-initial**: Initial value of highest imported power use in the year. Sets the minimum for demand charges to `demand-rate` * `p-max-initial`
- **import-max**: maximum power of commodity that can be imported per time-step
- **export-max**: maximum power of commodity that can be exported per time-step
- **operating-hours-min**: Minimum value for "operating hours" of import. Operating hours are calculated by dividing the total energy imported during one year by the highest imported power during a specific time period (`time-interval-demand-rate`) in the year. The highest possible value is the number of hours of one year (8760), which would lead to a constant import over the whole year (smooth load). This parameter can be used to model special demand charge tariffs, that require a minimum value for the operating hours for energy import. Set the value to zero to ignore this constraint.

Edit Example: The commodities `gas` and `elec` that can be imported/exported are already defined. Change the Value for the demand rate of the commodity `elec` to 10. Keep the other inputs as they are.

Table 1.3: Sheet **Ext-Commodities**

Commodity	demand-rate	time-interval-demand-rate	p-max-initial	import-max	export-max	operating-hours-min
elec	**10**	900	0	inf	inf	0
heat	0	900	0	inf	0	0

Ext-Import

Time-series: Costs for every commodity that can be imported for every time-step (in Euro/kWh).

Note: Positive values mean, that you have to **PAY** for imported energy

Edit Example: Set the costs for electricity import to 0.15 Euro/kWh and for gas import to 0.05 Euro/kWh for very time-step.

Table 1.4: Sheet **Ext-Import**

Time	elec	gas
1	**0.15**	**0.05**
2	**0.15**	**0.05**
3	**0.15**	**0.05**
4	**0.15**	**0.05**
5	**0.15**	**0.05**
6	**0.15**	**0.05**
7	...	...

Ext-Export

Time-series: Revenues for every commodity that can be exported for every time-step (in Euro/kWh).

Note: Positive values mean, that you **RECEIVE MONEY** for exported energy.

Edit Example: Set the revenues for electricty export to 0.01 Euro/kWh. Gas can not be exported because we limited the maximal power export to zero. So no time-series is needed.

Table 1.5: Sheet **Ext-Export**

Time	elec
1	**0.01**
2	**0.01**
3	**0.01**
4	**0.01**
5	**0.01**
6	**0.01**
7	...

Demand-Rate-Factor

Time-series: Factor to be multiplied with the demand rate to calculate demand charges for every time-step.

This allows to raise, reduce or turn off the demand rate for specific time-steps to consider special tariff systems. Set all values to `1`, for a constant demand rate

Edit Example: Keep all values at `1` for constant demand rates.

Table 1.6: Sheet **Demand-Rate-Factor**

Time	elec	gas
1	1	1
2	1	1
3	1	1
4	1	1
5	1	1
6	1	1
7	...	...

Process

- **Process**: Name of the process
- **Num**: Number of identical processes
- **class**: assign process to a Process Class, which allows to consider additional fees/subsidies for inputs or outputs of this class and total power/energy limits for the whole class
- **cost-inv**: Specific investment costs for new capacities (in Euro/kW)
- **cost-fix**: Specific annual fix costs (in Euro/kW/a)
- **cost-var**: Specific variable costs per energy throughput (in Euro/kWh)
- **cap-installed**: Already installed capacity of process (no additional investment costs) (in kW)
- **cap-new-min**: Minimum capacity of process to be build, if process is built. It is allays possible that the process isn't built at all. (in kW) (**Note**: only considered if `Min-Cap` in `MIP-Settings` is `True`)
- **cap-new-max**: Maximum new process capacity
- **partload-min**: Specific minimum part-load of process (normalized to 1 = max). (**Note**: only considered if `Partload` in `MIP-Settings` is `True`)
- **start-up-energy**: Specific additional energy consumed by the process for start-up (in kWh/kW). For each input commodity this value is multiplied by the `ratio` in `Process-Commodity` (**Note**: only considered if `Partload` in `MIP-Settings` is `True`)
- **initial-power**: Initial Power throughput of process for time-step t=0 (in kW)
- **depreciation**: Depreciation period. Economic lifetime (more conservative than technical lifetime) of a process investment in years (a). Used to calculate annuity factor for investment costs.
- **wacc**: Weighted average cost of capital. Percentage (%/100) of costs for capital after taxes. Used to calculate annuity factor for investment costs.

Note: All specific costs and capacities refer to the commodities with input or output ratios of `1`! For a process *Turbine* defined by the following table, all specific costs (e.g. Specific Investment Costs) correspond to the installed electric power. So if specific investment costs of 10 Euro/kW are given and a turbine with 10 kW electric output power is built, the investment costs are 100 Euro. The maximum input power of the commodity gas though is 300 kW!

Table 1.7: Example for input/output ratios of a process

Process	Commodity	Direction	ratio
Turbine	gas	In	3
Turbine	elec	Out	1

Edit Example: Delete all existing processes and add the new processes **chp**, **wind_1**, **wind_2** and **boiler**. Set the parameters as shown in the table.

Table 1.8: Sheet **Process**

Process	Num	class	cost-inv	cost-fix	cost-var	cap-installed	cap-new-min	cap-new-max	partload-min	start-up-energy	initial-power	depreciation	wacc
chp	1	CHP	700	0	0.01	0	0	1e6	0	0.0	0	10	0.05
wind_1	1	WIND	1000	0	0.005	0	0	1e6	0	0.0	0	10	0.05
wind_2	1	WIND	1000	0	0.005	0	0	1e6	0	0.0	0	10	0.05
boiler	1		100	0	0.001	0	0	1e6	0	0.0	0	10	0.05

Process-Commodity

Define input and output commodities and the conversion efficiencies between them for each process. Each commodities can have multiple inputs and outputs.

- **Process**: Name of the Process. Make sure that you use exactly the same name, than in sheet `Process`
- **Commodity**: Name of commodity that is used/produced by the process.
- **Direction**: *In* if the commodity is used by the process, *Out* if the commodity is produced.
- **ratio**: input/output ratios for the commodities of the process at full load.
- **partload-ratio**: input/output ratios for the commodities of the process at minimum part-load (`partload-min`) given in sheet `Process` (**Note**: only considered if `Partload` in `MIP-Settings` is `True` and `partload-min` is between 0 and 1)

Let's assume we defined a **chp** (combined heat and power) unit and set the minimum part-load to 50% (`partload-min=0.5`) in the *Process* sheet:

Table 1.9: Sheet **Process**

Process	Num	class	…	partload-min	…
chp	1	CHP	…	0.5	…

Now we want to define, that the chp unit consumes `gas` and produces electricity (`elec`) and `heat`. We want to set the electric efficiency to **40%** at full load and to **30%** at minimum part-load. The efficiency for generating heat should be **50%** at full load and **55%** at part-load.

Because specific costs and power outputs for chp units are usually given referred to the electric power output, we set the `ratio` **ans** `ratio-partload` of `(chp,elec,Out)` to **1**. (**Note**: All specific costs and capacities given in the `Process` sheet refer to the commodities with input or output ratios of `1`! See *Process*)

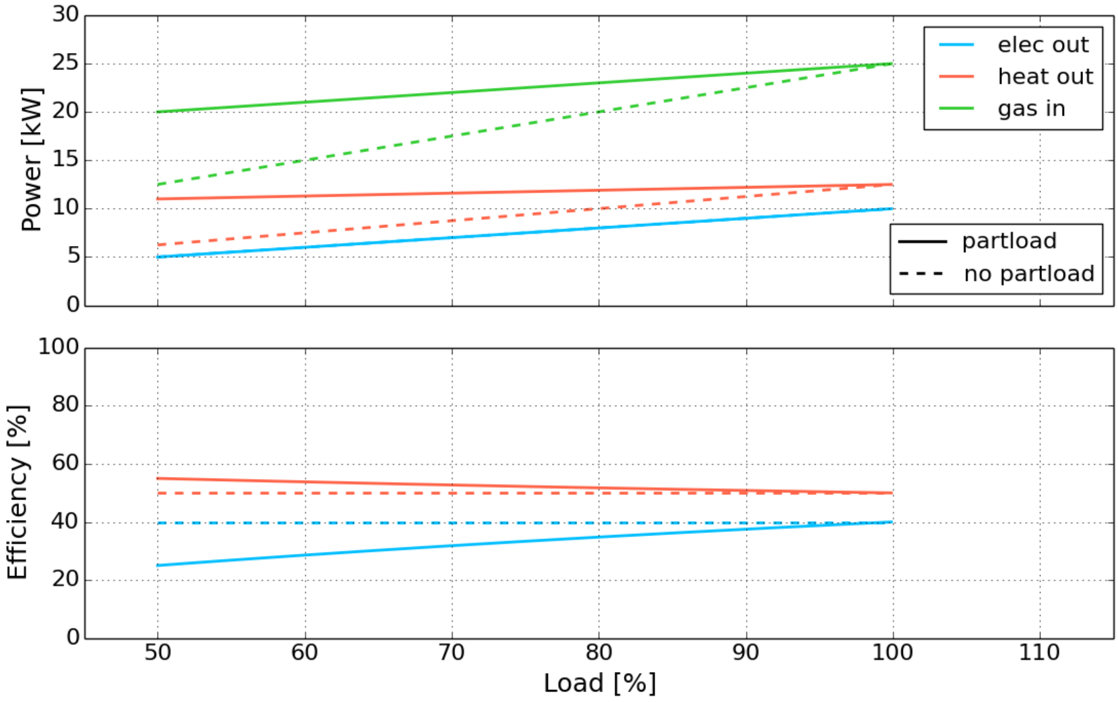
Now we can calculate the ratios of the other commodities based on the efficiencies, so we get:

Table 1.10: Sheet **Process-Commodity**

Process	Commodity	Direction	ratio	ratio-partload
chp	gas	In	2.50	4.00
chp	elec	Out	**1.00**	**1.00**
chp	heat	Out	1.25	2.20

So with setting the ratios for full load and minimum part-load we defined the part-load performance curve of our process. Points between full load and minimum part-load are approximated as a linear function between them. (**Note**: If `Partload` in `MIP-Settings` is set to `False`, part-load behaviour is not considered and the efficiencies defined by `ratio` are constant for all operating points. The values in `ratio-partload` are ignored).

The following figure shows the power inputs/outputs and efficiencies of a 10 kW (elec!) chp unit with the parameters used in this example with and without considering part-load behaviour.



Edit Example: Delete all existing processes and add the new processes **chp**, **wind_1**, **wind_2** and **boiler**. Set the ratios as shown in the table. Because part-load behaviour is not considered in this example, we just use the same values for `ratio-partload` (we could leave the `ratio-partload` column empty or set to any arbitrary value as long as `Partload` in `MIP-Equations` is deactivated)

Table 1.11: Sheet **Process-Commodity**

Process	Commodity	Direction	ratio	ratio-partload
chp	gas	In	2.50	2.50
chp	elec	Out	1.00	1.00
chp	heat	Out	1.25	1.25
wind_1	wind1	In	1.00	1.00
wind_1	elec	Out	1.00	1.00
wind_2	wind2	In	1.00	1.00
wind_2	elec	Out	1.00	1.00
boiler	gas	In	1.10	1.10
boiler	heat	Out	1.00	1.00

Process Class

Define a Process Class and add fees/subsidies for a produced/consumed commodity or capacity and energy limits for this class.

Processes can be assigned to a process class in the columns `class` in the `Process` sheet (See Process_ref). Make sure you use exactly the same names.

- **Class**: Name of the Process Class
- **Commodity**: Commodity of the processes within the class
- **Direction**: Direction of the commodity within the processes of this class (*In* or *Out*)
- **fee**: additional fee for produced/consumed energy in this class. (Positive values: Pay Money; Negative Values: Receive Money)
- **cap-max**: Maximum value for the sum of all process capacities of this class (Independent from `Commodity`)
- **energy-max**: Maximum value for the sum of energy of the specified commodity that can be produced/consumed by the class within one year

Edit Example: Delete all existing processes classes and add the new classes **CHP** and **WIND** with Commodity `elec` and Direction `Out`. Set the ratios as shown in the table. This sets a maximum of **20000 kW** for the total capacity of wind turbines, a subsidy of **0.05 Euro/kWh** for produced electricity of the wind turbines (weather sold to the grid or used to cover the demand) and a fee of **0.02 Euro/kWh** for produced electricity out of our chp unit.

Table 1.12: Sheet **Process-Class**

Class	Commodity Direction	fee	cap-max	energy-max	
CHP	elec	Out	0.02	inf	inf
WIND	elec	Out	-0.05	20000	inf

Storage

Define storages for a commodity with technical parameters and specific costs.

- **Storage**: Name of storage
- **Commodity**: Commodity that can be stored

- **Num**: Number of identical storages
- **cost-inv-p**: Specific investment costs for new charge/discharge power capacities of storage (in Euro/kW)
- **cost-inv-e**: Specific investment costs for new energy capacities of storage (in Euro/kWh).
- **cost-fix-p**: Specific annual fix costs per installed charge/discharge power (in Euro/kW/a)
- **cost-fix-e**: Specific annual fix costs per installed energy (in Euro/kWh/a)
- **cost-var**: Specific variable costs per energy throughput (in Euro/kWh)
- **cap-installed-p**: Already installed charge/discharge power capacity of storage (no additional investment costs) (in kW)
- **cap-new-min-p**: Minimum charge/discharge power capacity of storage to be build, if process is built. It is always possible that the storage isn't built at all. (in kW) (**Note**: only considered if `Min-Cap` in `MIP-Settings` is `True`)
- **cap-new-max-p**: Maximum new charge/discharge power capacity of storage (in kW)
- **cap-installed-e**:Already installed energy capacity of storage (no additional investment costs) (in kWh)
- **cap-new-min-e**: Minimum power capacity of storage to be build, if process is built. It is always possible that the storage isn't built at all. (in kWh) (**Note**: only considered if `Min-Cap` in `MIP-Settings` is `True`)
- **cap-new-max-e**: Maximum new energy capacity of storage (in kWh)
- **max-p-e-ratio**: Maximum relation of charge-discharge power to storage energy (in kW/kWh). power <= energy * ratio
- **eff-in**: Charge efficiency (in %/100)
- **eff-out**: Discharge efficiency (in %/100)
- **self-discharge**: Self discharge of storage (in %/h/100)
- **cycles-max**: Maximum number of full cycles before end of life of storage
- **DOD**: Depth of discharge. Usable share of energy of storage (in %/100)
- **initial-soc**: Initial state of charge of the storage (in %/100).
- **depreciation**: Depreciation period. Economic lifetime (more conservative than technical lifetime) of a process investment in years (a). Used to calculate annuity factor for investment costs.
- **wacc**: Weighted average cost of capital. Percentage (%/100) of costs for capital after taxes. Used to calculate annuity factor for investment costs.

Note: All values for the storage energy capacities and energy specific costs are related to the energy that can be **stored in the storage** with 100 % depth of discharge (DOD). The energy that can be used out of the storage might be less, depending on the `DOD` and the discharge efficiency `eff-out`.

Edit Example: Change the parameters of the storage **battery** and **heat storage** as shown in the table.

Table 1.13: Sheet **Storage** (1/3)

Storage	Commodity	Num	cost-inv-p	cost-inv-e	cost-fix-p	cost-fix-e	cost-var
battery elec	1	0	1000	0	0	0	
heat storage	heat	1	0	10	0	0	0

Table 1.14: Sheet **Storage** (2/3)

Storage	Commodity	Num	cap-installed-p	cap-new-min-p	cap-new-max-p	cap-installed-e	cap-new-min-e	cap-new-max-e	max-p-e-ratio
battery	elec	1	0	0	1e6	0	0	100000	2
heat storage	heat	1	0	0	1e6	0	0	30000	1

Table 1.15: Sheet **Storage** (3/3)

Storage	Commodity	Num	eff-in	eff-out	self-discharge	cycles-max	DOD	initial-soc	depreciation	wacc
battery	elec	1	0.900	0.900	0.0001	10000	1	0	10	0.05
heat storage	heat	1	0.950	0.950	0.0001	1000000	1	0	10	0.05

Demand

Time-series: (average) power demand for every commodity to be satisfied for every time-step (in kW).

Edit Example: Keep the demand time-series for `elec` and `heat` as they are

Table 1.16: Sheet **Demand**

Time	elec	heat
1	28749.52	8856
2	29383.66	8676
3	29496.09	9104
4	29592.54	8892
5	30346.42	8764
6	31300.91	8560
7	...	...

SupIm

Intermittent Supply: A time-series normalised to a maximum value of 1 relative to the installed capacity of a process using this commodity as input. For example, a wind power time-series should reach value 1, when the wind speed exceeds the modelled wind turbine's design wind speed is exceeded. This implies that any non-linear behaviour of intermittent processes can already be incorporated while preparing this time-series.

Edit Example: Copy the intermittent supply timeseries **wind1** and **wind2** from `intermittent_supply_wind.xlsx` to the `SupIm` sheet.

Table 1.17: Sheet **SupIm**

Time	wind1	wind2
1	0.91	1.00
2	1.00	1.00
3	1.00	1.00
4	1.00	1.00
5	1.00	1.00
6	0.88	1.00
7	…	…

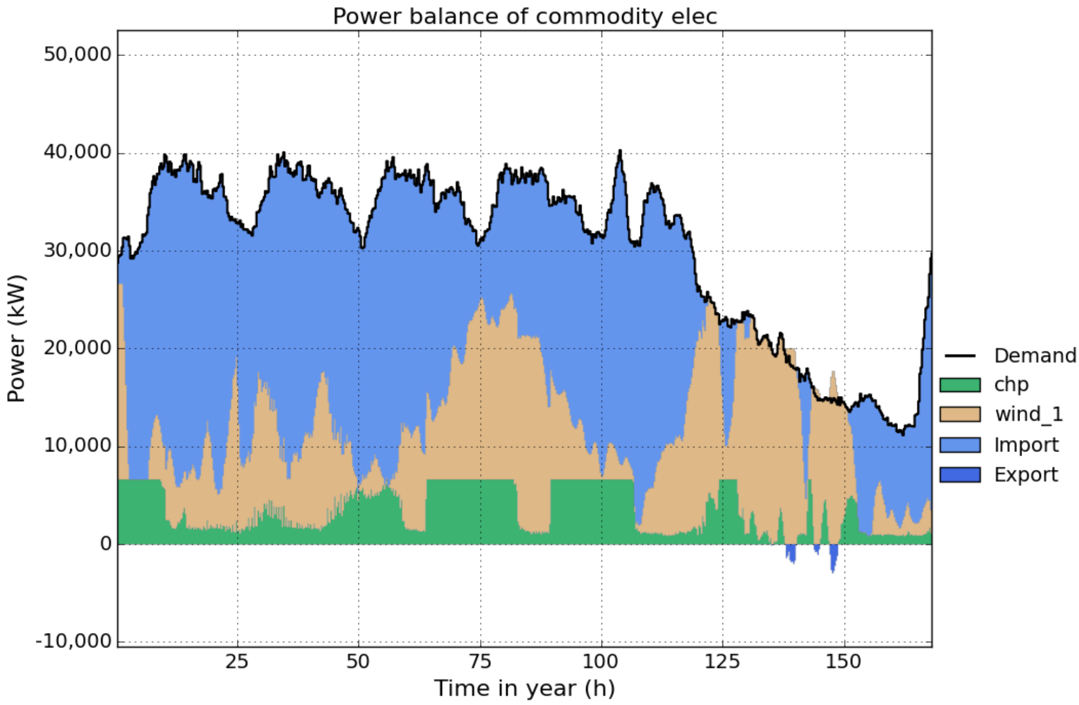
Note: For reference, this is how `NewFactory.xlsx` and `NewFactory.xlsm` look for me having performed the above steps.

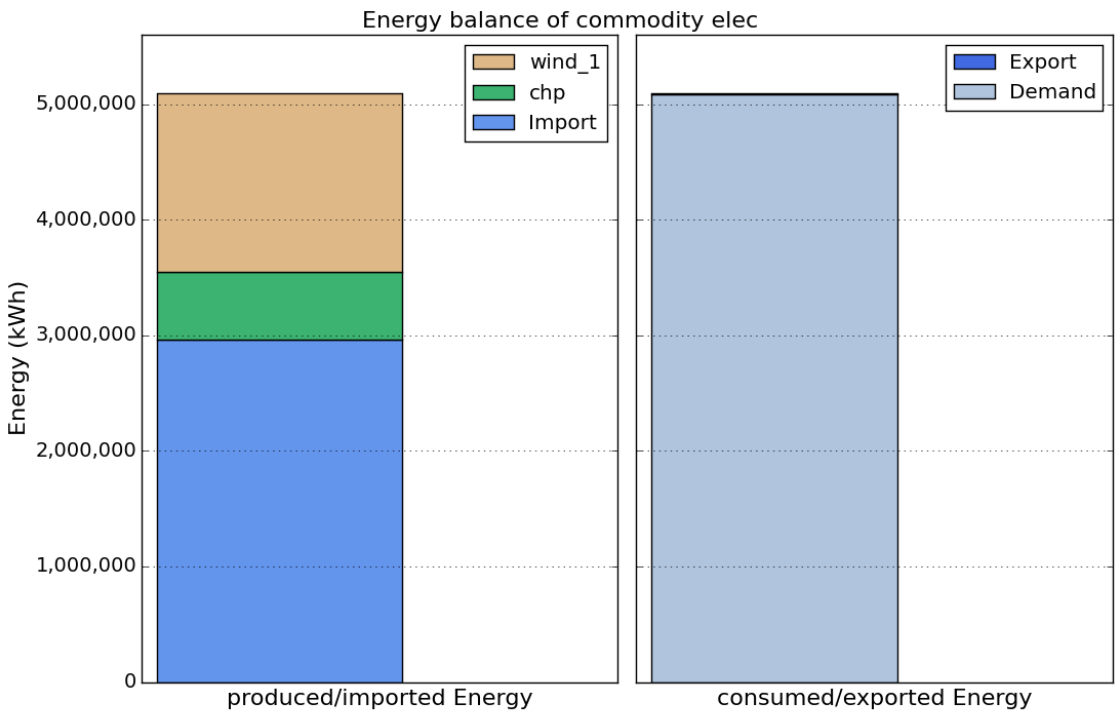
Test-drive the input

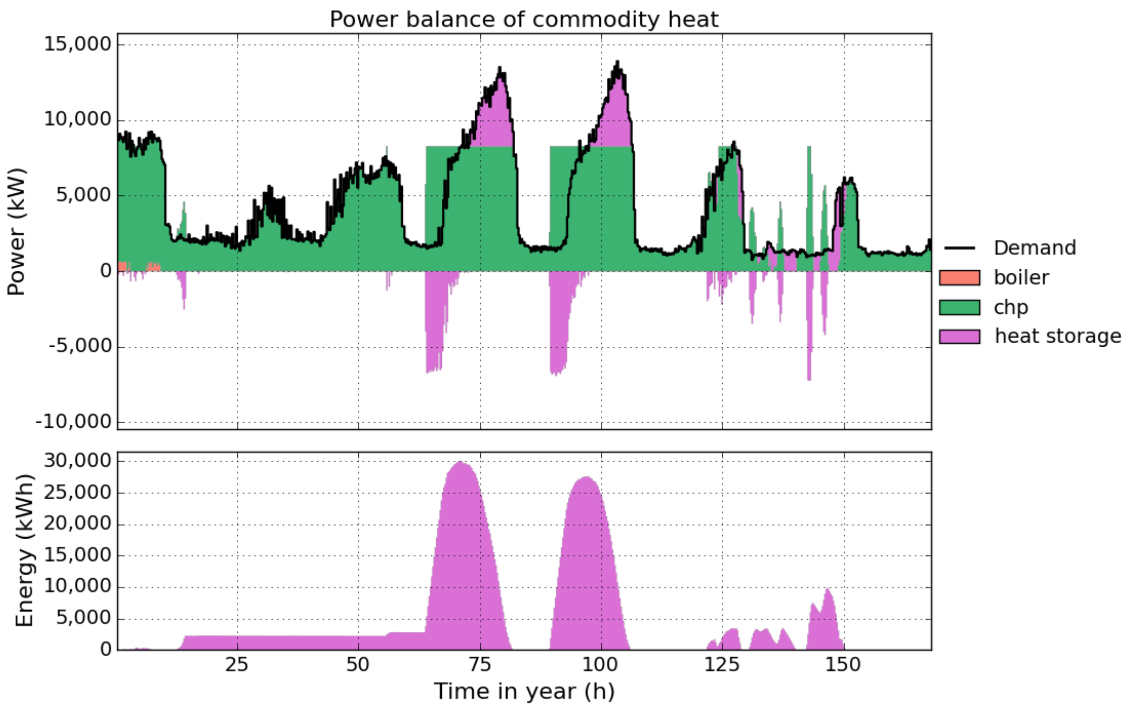
Now that `NewFactory.xlsx` or `NewFactory.xlsm` is ready to go, run the model:

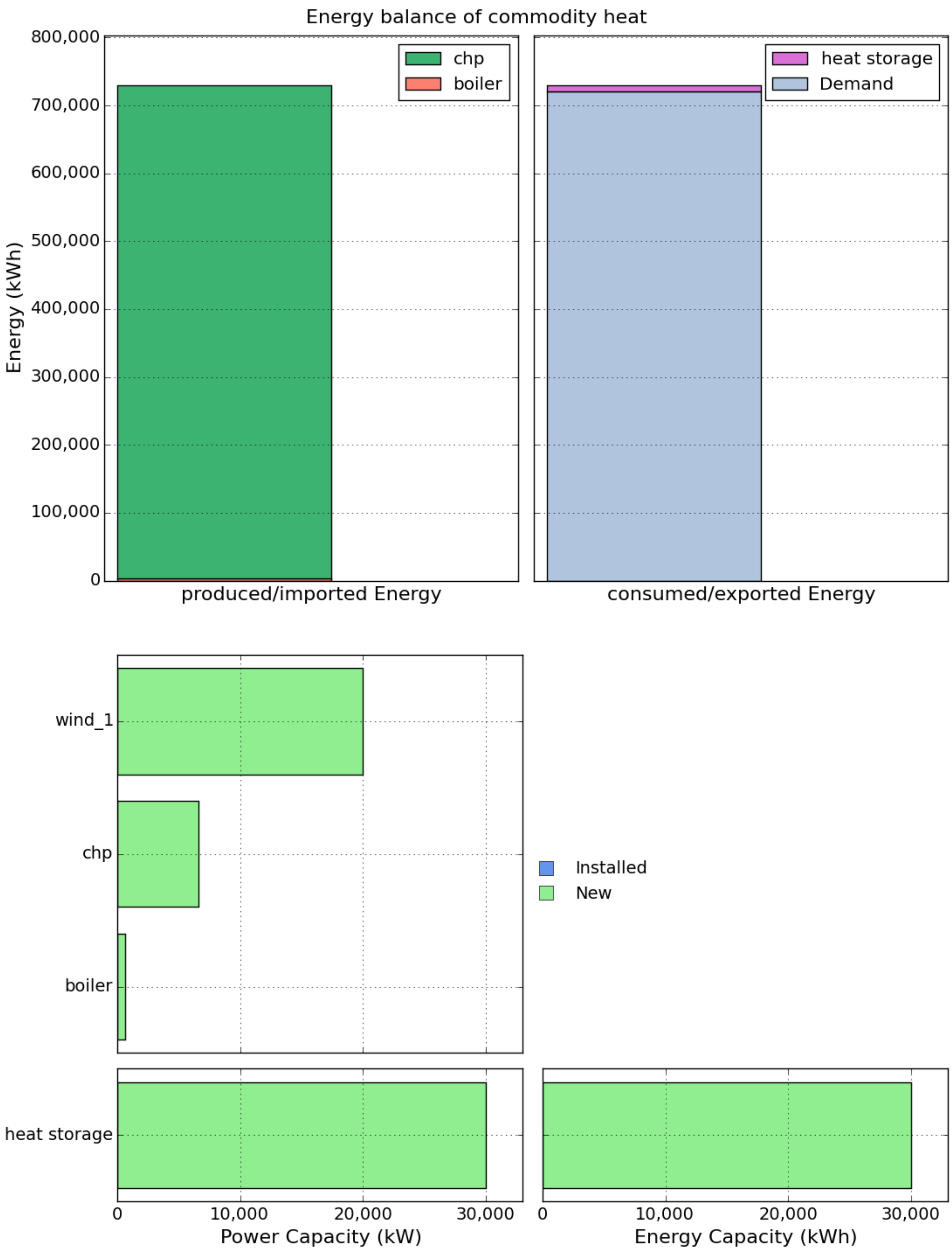
run-excel-ref or *Run from Python*

Th obtained results should look like this:

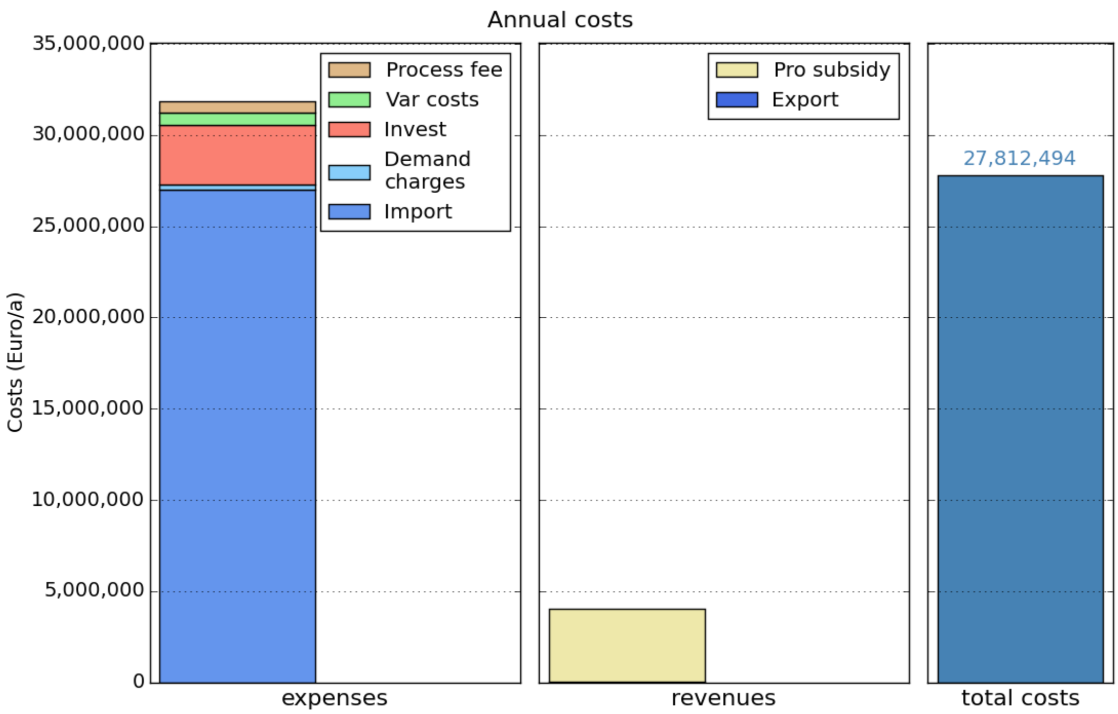



Energy balance of commodity elec
wind_1
chp
Import
Export
Demand
Energy (kWh)
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
produced/imported Energy
consumed/exported Energy


Power balance of commodity heat
Power (kW)
15,000
10,000
5,000
0
-5,000
-10,000
Demand
boiler
chp
heat storage
Energy (kWh)
30,000
25,000
20,000
15,000
10,000
5,000
0
25
50
75
100
125
150
Time in year (h)



Energy balance of commodity heat
Energy (kWh)
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
chp
boiler
heat storage
Demand
produced/imported Energy
consumed/exported Energy
wind_1
chp
boiler
heat storage
Installed
New
0
10,000
20,000
30,000
Power Capacity (kW)
Energy Capacity (kWh)



1.3.2 MIP-Equations

This sections shows the influence of the equations that can be activated/deactivated in the sheet `MIP-Equations` with the help of an example.

See *MIP-Equations* for a short Description.

Storage In-Out

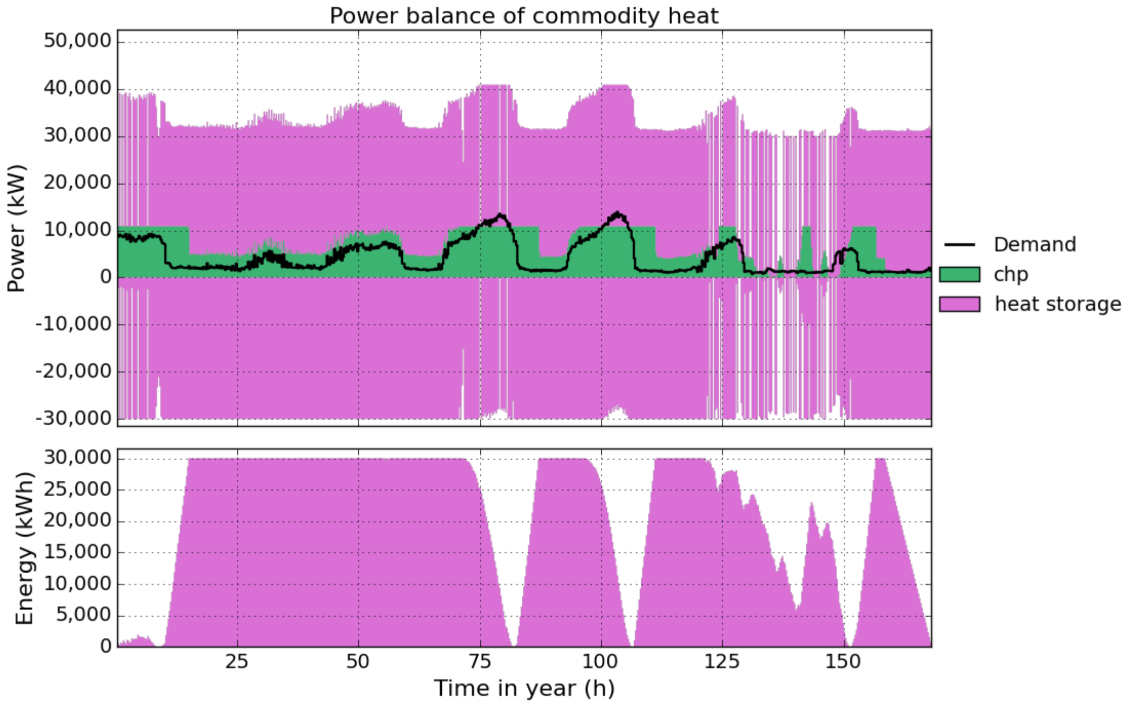
If activated, a constrained is added, that prevents storages from charging and discharging one commodity at the same time.

Open `NewFactory.xlsx` or `NewFactory.xlsm`, change the costs for gas import from **0.05 Euro/kWh** to **0.03 Euro/kWh**.

Table 1.18: Sheet **Ext-Import**

Time	elec	gas
1	0.15	**0.03**
2	0.15	**0.03**
3	0.15*	**0.03**
4	0.15	**0.03**
5	0.15	**0.03**
6	0.15	**0.03**
7	…	…

Save the new file and run the model. Take a look at the `heat` time-series result figure:



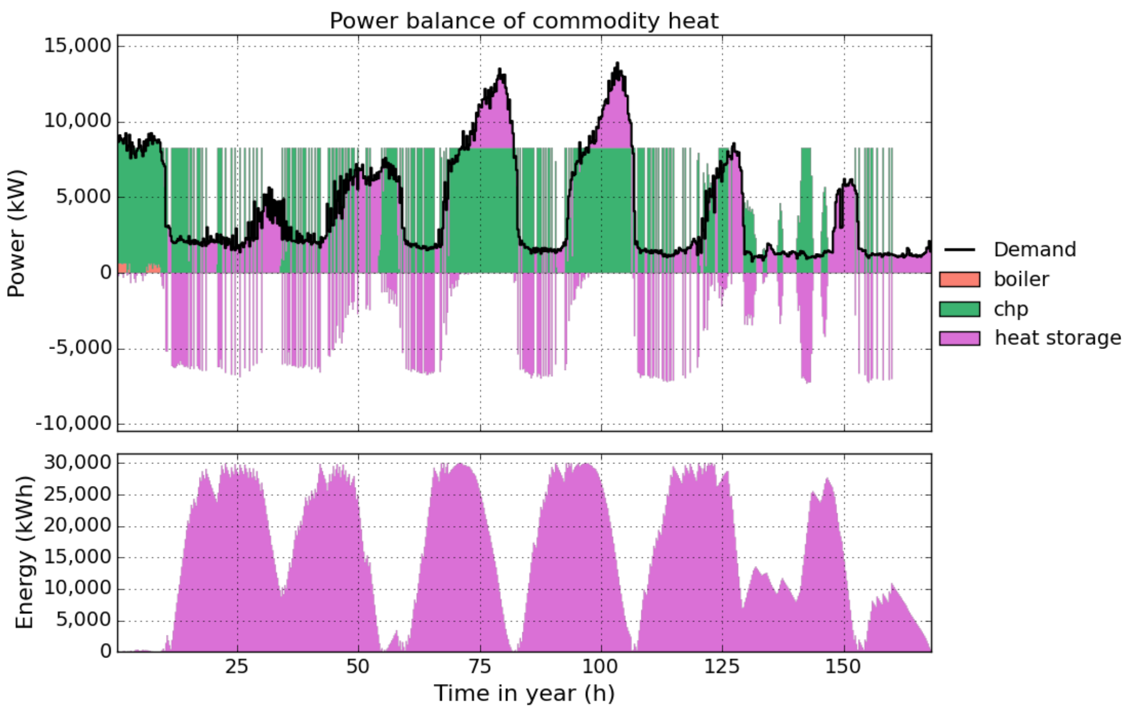
As you can see the heat storage is charged and discharged at the same time for almost the whole period. This is because of the low gas costs producing electricity from the chp unit becomes much cheaper than importing it from the grid. The model tries to produce as much electricity from the chp unit as possible, but is limited because of the lower heat demand (the produced heat has to be consumed as well). The model equations do **not** allow dumping energy. So to get rid of the heat produced, th model uses the heat storage efficiency to generate losses by simply charging and discharging at the same time.

To avoid this, activate `Storage In-Out` in the sheet `MIP-Equations`:

Table 1.19: Sheet **MIP-Equations**

Equation	Active
Storage In-Out	**yes**
Partload	no
Min-Cap	no

Run the model again. This will take a little more time than before, because the equation uses an integer variable and the model becomes a mixed integer linear optimisation problem. Looking at the `heat` time-series result figure again, you can see that charging/discharging of the storage at the same time is avoided now.



Partload

If activated, minimum part-load settings, part-load efficiencies as well as start-up costs of processes are considered.

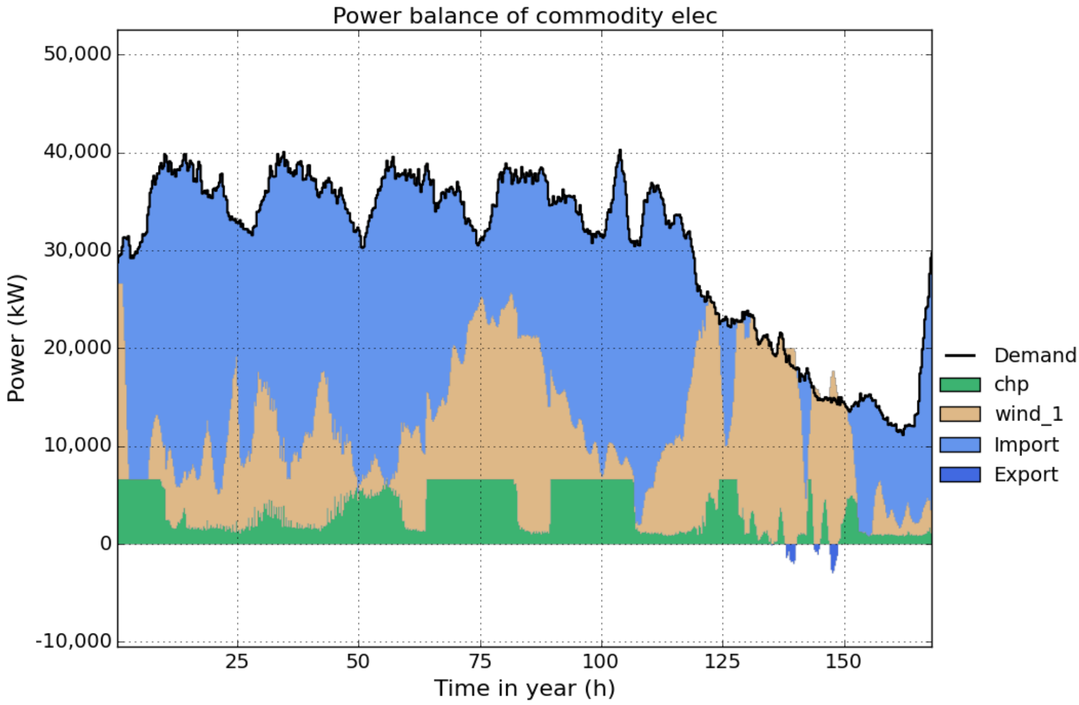
Open `NewFactory.xlsx` or `NewFactory.xlsm`.

To reduce computation time, we assume that we already have a chp unit with a capacity of 7,000 kW in our factory and do not allow to build more capacity for this process. Therefore we change the parameters `cap-installed` and `cap-new-max` in the `Process` sheet as shown in the table below.

Table 1.20: Sheet **Process**

Process	Num	...	cap-installed	cap-new-min	cap-new-max	partload-min	start-up-energy	...
chp	1	...	**7000**	0	0	0	0	...
wind_1	1	...	0	0	1e6	0	0	...
wind_2	1	...	0	0	1e6	0	0	...
boiler	1	...	0	0	1e6	0	0	...

Save the input file, run the model and take a look at the `elec` timeseries result figure.



Now we want to implement a minimum partload for the chp unit. Therefore we set the parameter `partload-min` for the chp unit in the `Process` sheet to **0.5**. That means, if the chp unit is running, it has to run at minimum 50% of its rated (installed) power.

Table 1.21: Sheet **Process**

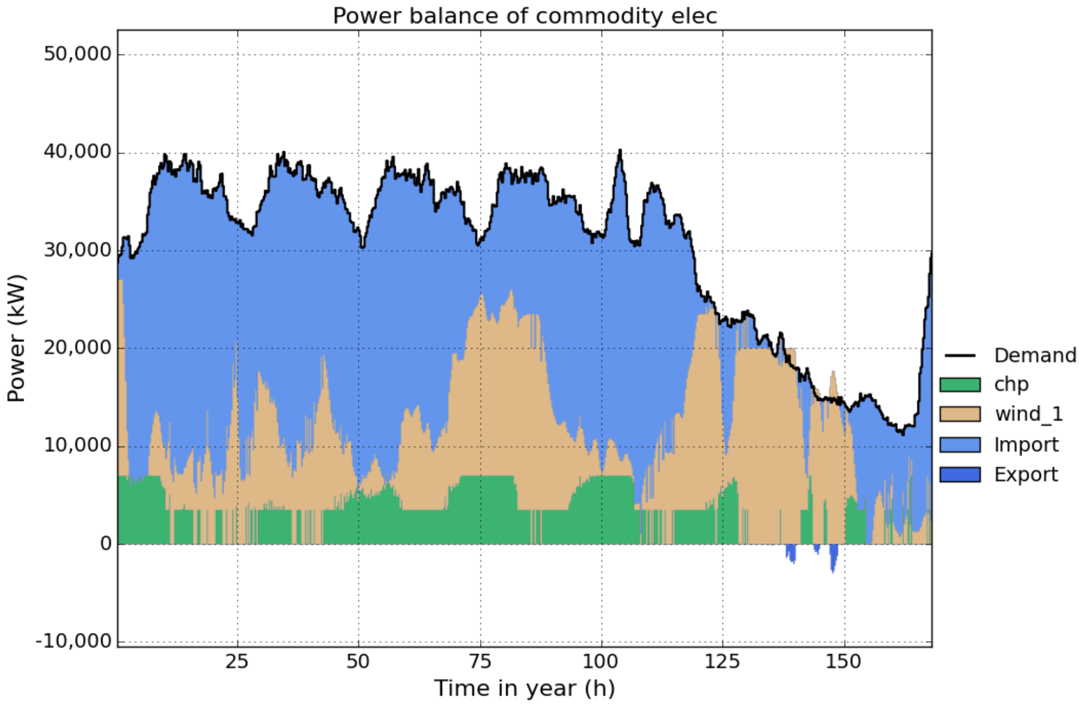
Process	Num	...	cap-installed	cap-new-min	cap-new-max	partload-min	start-up-energy	...
chp	1	...	7000	0	0	**0.5**	0	...
wind_1	1	...	0	0	1e6	0	0	...
wind_2	1	...	0	0	1e6	0	0	...
boiler	1	...	0	0	1e6	0	0	...

To activate this constrained , we have to activate `Partload` in the sheet `MIP-Equations`.

Table 1.22: Sheet **MIP-Equations**

Equation	Active
Storage In-Out	no
Partload	**yes**
Min-Cap	no

Now run the model and take a look at the `elec` time-series result figure again. You can see that the electric power output of the chp now is always greater than 50% of the installed capacity (7000 kW), when the chp unit is running.



In the next step we want to see the influence of considering part-load efficiency. Therefore we change the `ratio-partload` values in the `Process-Commodity` sheet as shown below , without changing the values in `Process` sheet. With this changes the chp unit has an electric (thermal) efficiency of **40%** **(50%)** at full load and **30%** **(55%)** at minimum part-load (50% of max. power). See *Process-Commodity* for detailed information. (**Note:** part-load efficiency can only be considered if `partload-min` is greater than zero.)

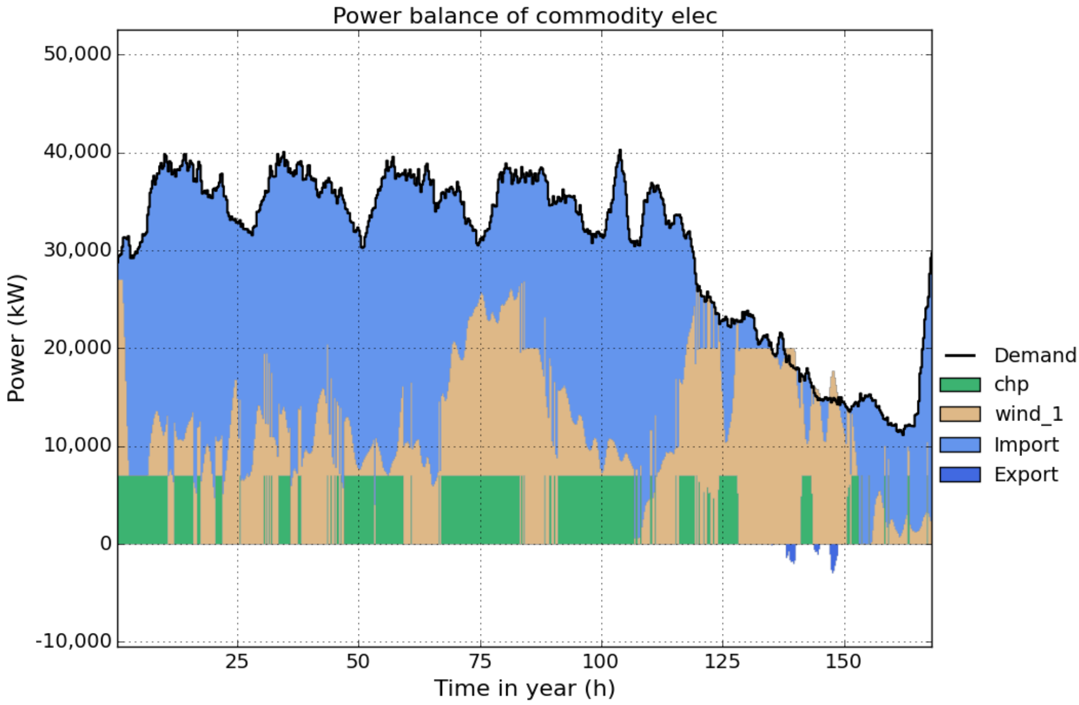
Table 1.23: Sheet **Process**

Process	Num	...	cap-installed	cap-new-min	cap-new-max	partload-min	start-up-energy	...
chp	1	...	7000	0	0	0.5	0	...
wind_1	1	...	0	0	1e6	0	0	...
wind_2	1	...	0	0	1e6	0	0	...
boiler	1	...	0	0	1e6	0	0	...

Table 1.24: Sheet **Process-Commodity**

Process	Commodity	Direction	ratio	ratio-partload
chp	gas	In	2.50	**4.00**
chp	elec	Out	1.00	1.00
chp	heat	Out	1.25	**2.2**

Run the model and take a look at the `elec` time-series result figure again. You can see how the model tries to run the chp unit at full load as much as possible to benefit from it's better electric efficiency at full load and reduce costs for gas import.

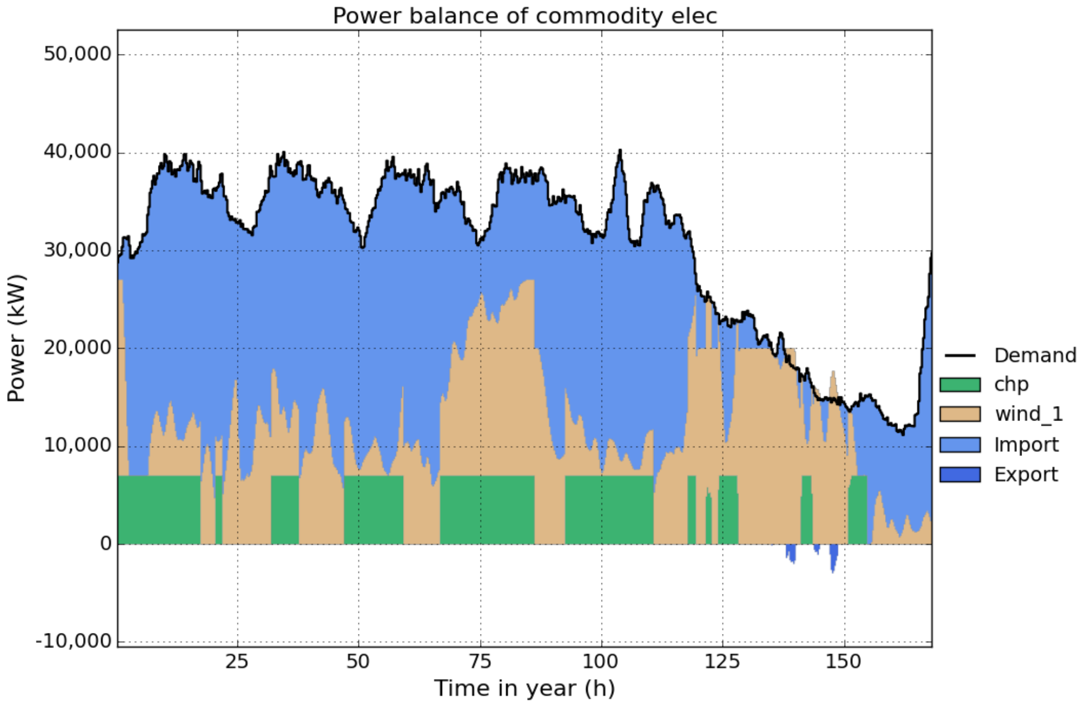


In the last step we add start-up costs for the chp unit, by setting the parameter `start-up-energy` in the `Process` sheet to **0.1 kWh/kW**. This means, that for every start-up all input commodities (here gas) consume 0.1 kWh * `ratio` (here 0.1*2.5 kWh) per installed capacity of the process. (**Note:**Start-up costs only occur, if `partload-min` is greater than zero.

Table 1.25: Sheet **Process**

Process	Num	...	cap-installed	cap-new-min	cap-new-max	partload-min	start-up-energy	...
chp	1	...	7000	0	0	0.5	**0.1**	...
wind_1	1	...	0	0	1e6	0	0	...
wind_2	1	...	0	0	1e6	0	0	...
boiler	1	...	0	0	1e6	0	0	...

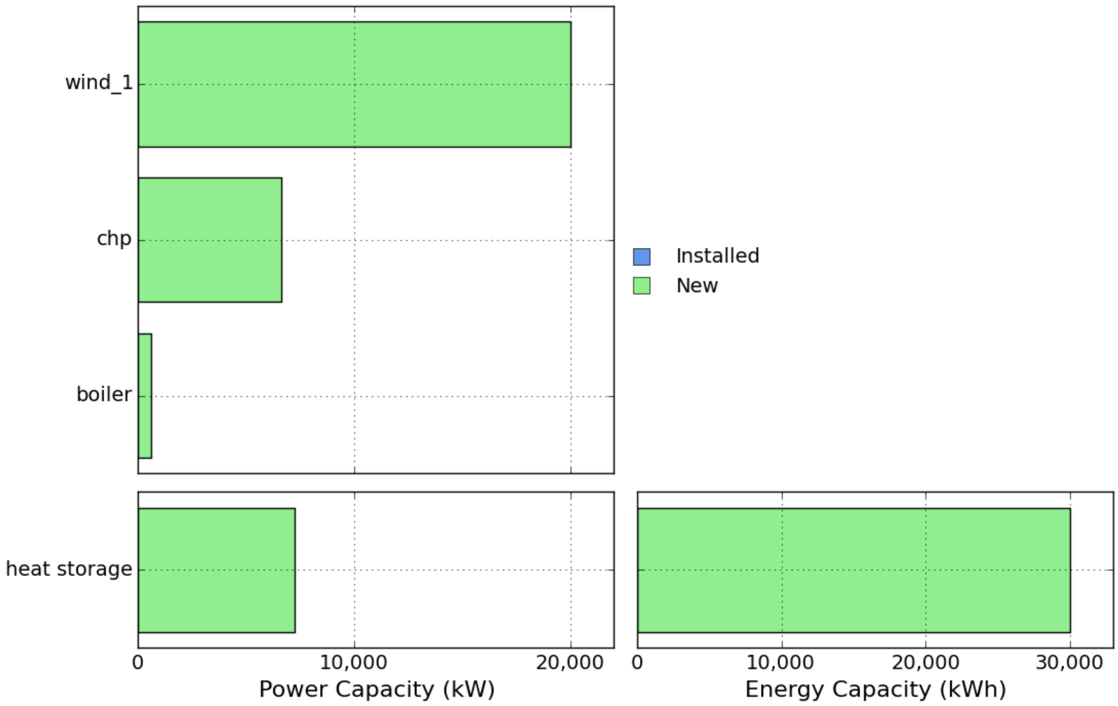
Run the model and take a look at the `elec` time-series result figure again. You can see how the number of start-up's is reduced to minimize start-up costs.



Min-Cap

Consider minimal installed capacities of processes and storages if activated. This allows to set a minimum capacity of processes and storages, that has to be build, if the process is built at all (it still can not be built at all). Setting minimal and maximal capacities of processes/storages to the same level, this allows investigating if building a specific process/storage with a specific size is cost efficient.

Open and run `NewFactory.xlsx` or `NewFactory.xlsm`, and take a look at the `capacities` result figure:



Now we want to know, if a chp unit with exactly 10,000 kW is cost-efficient for our factory. Therefore we change the `cap-new-min` and the `cap-new-max` parameter in the `Process` sheet to **10,000 kW**.

Table 1.26: Sheet **Process**

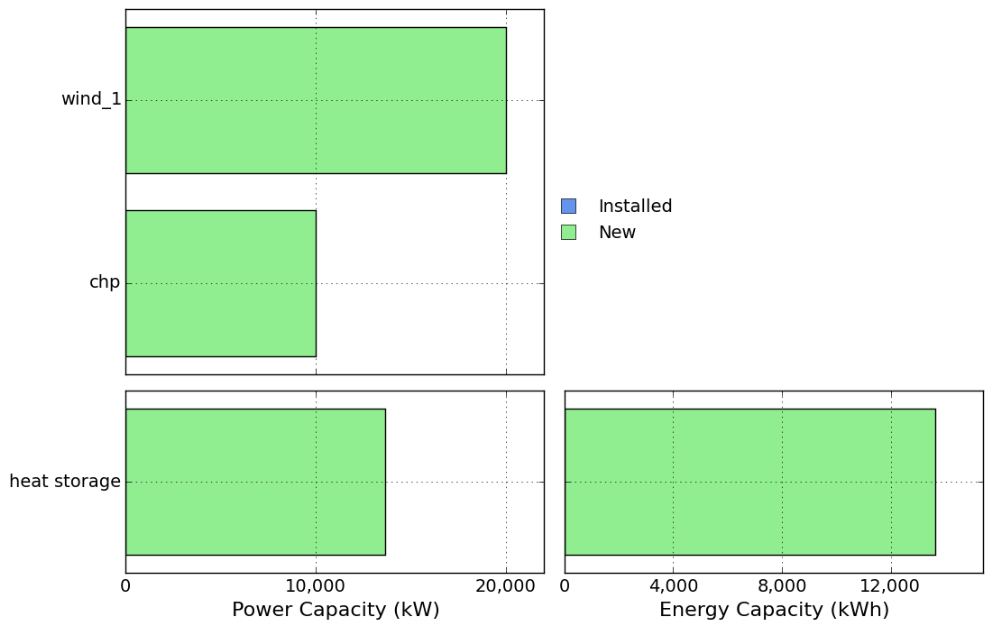
Process	Num	...	cap-installed	cap-new-min	cap-new-max	...
chp	1	...	0	**10000**	**10000**	...
wind_1	1	...	0	0	1e6	...
wind_2	1	...	0	0	1e6	...
boiler	1	...	0	0	1e6	...

To activate this constraint , we have to activate `Min-Cap` in the sheet `MIP-Equations`.

Table 1.27: Sheet **MIP-Equations**

Equation	Active
Storage In-Out	no
Partload	**yes**
Min-Cap	no

Running the file with the above changes show the following `capacities` result figure, You can see, that a chp unit with exactly 10,000 kW is built.



1.4 Examples

In the `examples` folder several examples of input files are given. This section gives a short description of the examples.

1.4.1 example.xls and example_from_excel.xlsm

The input file `example.xls` and `example_from_excel.xlsm` are used within the *tutorial* explaining how to create an own input file by editing a given one.

The factory described in this example has given demand time-series for electricity (*elec*) and *heat*, that have to be covered. While *elec* can be imported and exported, *heat* has to be produced inside the factory. Therefore an electric heater, a gas boiler and/or chp unit can be used. Since the chp and the gas boiler require *gas* as an input, *gas* can be imported as well. To model a *pv* system, the intermittend supply time-series *solar* is given. Additionally a battery storage for *elec* and a heat storage for *heat* are defined.

The processed chp, booiler and el. heater have given installed capaities that can not be expanded any more. Only the process pv and the battery and heat storage can be built. The result of this model will be an optimal cpacity expansion of this three technologies and an optimal operation of all defined and built processes and storages.

Table 1.28: Commodities defined in example.xls

Commodity	defined as	description
elec	import; export; demand	electricity
heat	demand	heat
gas	import	gas
solar	intermittend supply	time-series representing normalized output of a pv system

Table 1.29: Processes defined in example.xls

Process	inputs	outputs	intalled capacity	max new capacity
chp	gas	elec; heat	5000 kW	0 kW
boiler	gas	heat	15000 kW	0 kW
pv	solar	elec	0 kW	50000 kW
el. heater	elec	heat	500 kW	0 kW

Table 1.30: Storages defined in example.xls

Storage	commodity	intalled capacity	max new capacity
battery	elec	0 kW; 0 kWh	1000000 kW; 1000000 kWh
heat storage	heat	0 kW; 0 kWh	20000 kW; 20000 kWh

1.4.2 cover_heat+elec_xxx.xls

The input files `cover_heat+elec_automotive.xls`, `cover_heat+elec_carbon.xls`, `cover_heat+elec_iron.xls` and `cover_heat+elec_steel.xls` all have the same structure of defined commodities, processes and storages. But each factory has different demand time-series for electricity and heat. Since the time-series are given in a 15-minute resolution for one year, solving these problems might take a few hours (depending on the use solver).

The factories described in this example have given demand time-series for electricity (*elec*) and *heat*, that have to be covered. While *elec* can be imported and exported, *heat* has to be produced inside the factory. Therefore an immersion heater (im heater), a gas boiler and/or chp unit can be used. Since the chp and the gas boiler require *gas* as an input, *gas* can be imported as well. To model capacity specific investment costs, several chp units with different investment costs and different minimum new capacities are defined. Additionally three battery storages, *RedoxFlow*, Li-Ionen-1C* and *Li-Ionen-2C* for the commodity *elec* and a heat storage *TES* for *heat* are defined.

In these examples no processes and storages have installed capacities. The result of this model will be an optimal cpacity expansion and operation of all defined and built processes and storages. For importimg electricity here time-sensitive prices are used.

Table 1.31: Commodities defined in cover_heat+elec_xxx.xls

Commodity	defined as	description
elec	import; demand	electricity
heat	demand	heat
gas	import	gas
solar	intermittend supply	time-series representing normalized output of a pv system

Table 1.32: Processes defined in cover_heat+elec_xxx.xls

Process	inputs	outputs	intalled capacity	max new capacity
chp 10-1000	gas	elec; heat	0 kW	50000 kW
boiler	gas	heat	0 kW	50000 kW
el. heater	elec	heat	0 kW	50000 kW

Table 1.33: Storages defined in cover_heat+elec_xxx.xls

Storage	commodity	intalled capacity	max new capacity
battery	elec	0 kW; 0 kWh	500000 kW; 5000000 kWh
heat storage	heat	0 kW; 0 kWh	500000 kW; 5000000 kWh

1.4.3 steel_mill_example.xls

The factory described in this example describes an examplary steel mill. The steel mill has given demand time-series for electricity (*elec*), *heat* and *steel*, that have to be covered. While *elec* can be imported and exported, *heat* and *steel* have to be produced inside the factory.

For producing *heat* an immersion heater (im heater), a gas boiler and/or chp unit can be used. Since the chp and the gas boiler require *gas* as an input, *gas* can be imported as well. Both processes also are defined to produce *CO2* as an output commodity. Since the produced *CO2* has to be “used” somewhere, it is defined as an export commodity. By defining negative costs for exporting *CO2*, cost for *CO2* production is applyed here.

A battery storage for *elec* and a heat storage for *heat* are defined.

For producing steel, a electric arc furnace is defined. It consumes *iron*, which can be imported and *elec* to produce steel. Since there is a demand for *steel* only at the end of each working day, the steel could either produced at exactly at this time, or it can be produced during the whole day and stored in the defined stock. This leads to a smaller capacity of the furnace.

Additionally a battery storage for *elec* and a heat storage for *heat* are defined.

In these examples no processes and storages have installed capacities. The result of this model will be an optimal cpacity expansion and operation of all defined and built processes and storages. For importimg electricity here time-sensitive prices are used.

Table 1.34: Commodities defined in steel_mill_example.xls

Commodity	defined as	description
elec	import; export; demand	electricity
heat	demand	heat
gas	import	gas
solar	intermittend supply	time-series representing normalized output of a pv system
iron	import	iron ore used for steel production
steel	demand	steel that has to be produced
CO2	export	CO2 produced by the processes

Table 1.35: Processes defined in steel_mill_example.xls

Process	inputs	outputs	intalled capacity	max new capacity
chp	gas	elec; heat	0 kW	50000 kW
boiler	gas	heat	0 kW	50000 kW
pv	solar	elec	0 kW	200 kW
im heater	elec	heat	0 kW	50000 kW
furnace	elec;iron	steel	0 kW	50000 kW

Table 1.36: Storages defined in steel_mill_example.xls

Storage	commodity	intalled capacity	max new capacity
battery	elec	0 kW; 0 kWh	500000 kW; 5000000 kWh
heat storage	heat	0 kW; 0 kWh	500000 kW; 5000000 kWh
stock	steel	0 kW; 0 kWh	500000 kW; 5000000 kWh

CHAPTER 2

Features

- ficus is a (mixed integer) linear programming model for multi-commodity energy systems.
- It finds the minimum cost energy system to satisfy given demand time-series for possibly multiple commodities (e.g. electricity, heat)
- It considers given cost time-series for external obtained commodities as well as peak demand charges with configurable timebase for each commodity
- It allows to deactivate specific equations, so the model becomes a linear programming model without integer variables
- It supports multiple-input and multiple-output energy conversion technologies with load dependent efficiencies
- ficus includes reporting and plotting functions

CHAPTER 3

Installation

If you don't already have an existing Python I recommend using the Python distribution Anaconda. It contains all needed packages except Pyomo.

1. Anaconda (Python 2.7 or Python 3.5). Choose the 64-bit installer if possible. During the installation procedure, keep both checkboxes "modify PATH" and "register Python" selected!
2. Pyomo (pip install pyomo)
3. download or clone (with git) this repository to a directory of your choice.
4. Copy the `ficus.py` file to a directory which is already in python's search path or add the `python` folder to python's search path (sys.path) (how to)
5. Install a *solver* (optional).

CHAPTER 4

Get started

1. *Run* the given examples in the *examples* folder.
2. Follow the *turorial* to create your own input file.

CHAPTER 5

Solver

Pyomo allows using the NEOS Server for Optimization for solving, so it is **not required to install a solver**.

I still recommend to install and use one of the following solvers.

1. **GLPK (open source)**

   (a) Download the latest version (e.g. GLPK-4.55) of WinGLPK

   (b) Extract the contents to a folder, e.g. *C:GLPK*

   (c) Add the sub-folder *w64* to your system path, e.g. *C:GLPKw64* (how).

2. **CPLEX** (commercial)

   Download and install IBM's CPLEX solver. (Free for academics)

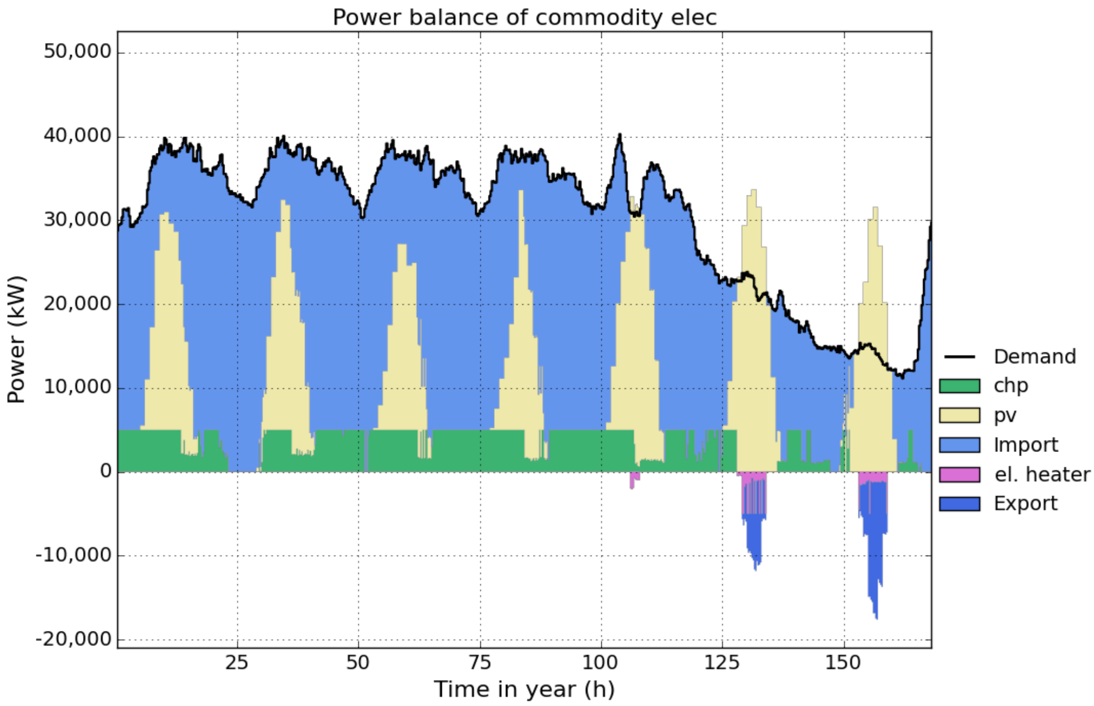
3. **Gurobi** (commercial)

   Download and install Gurobi solver. (Free for academics)

CHAPTER 6

Screenshots

This is a typical result plot created by `ficus.plot_timeseries()`, showing electricity generation and consumption over 7 days:



Python Module Index

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