MTRESS 3.0 – Modell Template for Residential Energy Supply Systems *

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Abstract

MTRESS is a tool that facilitates the creation of models of residential energy supply systems by providing a template with meaningful presets. This model can then be used to linearly optimise the operation of the energy system. Version 3.0 enables multiple locations belonging to one energy system to be defined. Furthermore, it adds hydrogen as an energy carrier with the possibility to convert power to gas using electrolysis and to store gas at different pressure levels. Additionally, we reworked the Python API, giving more flexibility to the user.

1 Introduction

Graph based formulation of an energy system in order to formulate a (mixed-integer) linear optimisation problem can be considered a standard approach. In Python, there are several tools implementing that approach. For example, there are PyPSA [1], urbs [2], OSeMOSYS [3], PowerGAMA [4], Minpower [5], MOST [6], Calliope [7], and oemof.solph [8]. It is also noteworthy that they have similar dependencies, i.e. most are based on Pyomo [9][10]. As a result, improvements to one of those tools can be adapted for the others.

The present contribution aims to further simplify the creation of this kind of models, even when the level of detail is increased. Also, it offers different styles of creating energy system models, either by preparing formatted data in text files or by scripting in Python. The implementation of these styles is influenced

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by the aforementioned tools Calliope and oemof.solph. Calliope emphasises a strict separation of data and program, and considers the definition of a model as data that is parameterised using text files in YAML and CSV formats. On the other hand, oemof.solph implements a "create and add" workflow, so that implementation of the specific model and the data are located closely to one another in the code.

2 Architecture of MTRESS 3.0

The aim of MTRESS is the simple creation of energy supply system models while keeping model accuracy at a considerably high level. To give meaningful presets, a number of assumptions is made that are often met. With MTRESS 3.0, a number of new concepts is introduced to allow for more flexibility compared to previous versions. Further – as MTRESS wraps oemof.solph – energy systems created using the template can also be extended and further refined using the full flexibility of oemof.solph.

The overall structure is created by building blocks of the five classes EnergySystem, Location, EnergyCarrier, Component, and Demand. One major simplification compared to other methods to create energy system models is that the connections do not have to be defined by the user.

2.1 Energy System

The EnergySystem serves as a container for the model. It holds global information, e.g. about the time, and defaults that can be overwritten for specific locations, e.g. weather data. Furthermore, all locations of the model and the connections between them are registered with the EnergySystem object. Once the energy system is about to be solved, it makes sure every location has all the necessary connections and constraints set.

2.2 Location

A Location collects different energy carriers, components and demands.

To allow for automatic connections between the components and demands, every energy carrier (e.g. electricity or heat) and every component (e.g. a heat pump) can only be defined once per location (or left out). To define multiple instances of one energy carrier with different configurations, multiple locations have to be defined.

2.3 Energy Carrier

Each EnergyCarrier represents a form of energy in an energy systems location and acts as a distribution hub between components. Currently, electricity, heat, natural gas, and hydrogen are implemented. These energy carriers may have a "grid connection", meaning that energy may be purchased or sold. Currently, the following energy carriers are implemented:
Electricity  Electricity is implemented in a way that allows the tracking of which energy is used where. While there is no physical difference, the model distinguishes between electricity that is produced locally and electricity coming from the grid. This enables different fees and tariffs based on the origin of the electricity to be considered.

Heat  The temperature has a significant impact on the performance of renewable energy supply systems, e.g. for the Coefficient of Performance (COP) of heat pumps or the output of a solar thermal collector. Thus, the energy carrier heat allows to optimise both temperature and heat. This is done by defining several discrete temperature levels. Besides the temperature levels, a reference temperature can be defined. This can be useful to simplify the model by setting the reference to a return temperature, resulting in the corresponding return flow to be considered at zero energy. Some temperatures, i.e. the ones of sources for heat pumps, are not considered by the energy carrier. To emphasise that fact, these sources are defined as anergy sources, which are not connected to the energy carrier but only to the heat pump.

Gas  The concept of the energy carrier heat is expanded to (compressible) gas. It can be expanded from high pressure to lower pressure or compressed (using a compressor). The pressure level plays a role, especially when energy is stored in gaseous form.

As hydrogen was recently implemented into MTRESS in the form of an electrolyzer and a hydrogen compressor, the gas carrier currently finds application in that field.

2.4 Component

A Component represents a technology used in the system. They can serve as sources or connect either energy carriers to each other or different temperature levels (in case of the heat carrier) or pressure levels (in case of a gaseous carrier) of the carrier. The following collection of components should give an idea of the concept:

Heat Pump  The heat pump uses electricity and provides heat (possibly at different temperature levels). Further, it connects to every available anergy source at the location. The COPs are automatically calculated based on the information given by the heat carrier and the anergy sources.

Anergy Sources  There can be several anergy sources, e.g. down hole heat exchangers or air source heat exchangers. They hold a time series for both the temperature and the power limit that can be drawn from the source. Furthermore, additionally a total limit can be defined. This is particularly important for geothermal sources that need to recover.
Combined Heat and Power  Combined heat and power (CHP) units consume gas and supply both heat and electricity. It is possible to choose between different models that linearize the CHP to consider (or neglect) nonlinear part-load efficiencies.

Renewable Electricity Source  Renewable electricity sources are representing photovoltaic (PV), wind power, or river-flow water generators. They contain a time series for the maximum power that can be drawn from them. For PV, the time series can be automatically calculated by MTRESS from a weather time series.

Energy storage  Energy storage is implemented per carrier. Thus, there can be electricity storage (battery), heat storage, and gas storage. The three types incorporate the properties of the corresponding energy carrier. The battery is represented by a state of charge. We decided to not allow changing voltage levels for the electricity, as this technical option is typically not implemented. For heat storage and gas storage, stored content depends on an optimisation variable (temperature or pressure), the used linearization is described in Sec. 3.

PEM Electrolyzer  In regard to the generation of hydrogen, a proton-exchange-membrane (PEM) electrolyzer was implemented. It uses electricity and water (H\textsubscript{2}O) to produce hydrogen (H\textsubscript{2}) and oxygen (O). For the simplicity of the model, water-input as well as oxygen-output can be neglected. However, the usage of waste heat generated by the electrolyzer was implemented into the model. Usually waste-heat of PEM electrolyzers is produced at 77°C \cite{12}, while hydrogen is produced at a pressure of around 30 bar \cite{13}.

Compressor  To consider the necessity for different pressure levels of hydrogen, e.g. for transport or usage at the maximum density of 700 bar or a storing at 350 bar for rocket science applications \cite{14}, a compressor was implemented. The compressor uses electricity to rise the pressure level of the produced hydrogen.

2.5 Demand

Demands contain time series of energy that is needed. Depending on the type of demand (e.g. electricity or heat), it automatically connects to the corresponding energy carrier. Also, a name identifying the demand has to be given that is unique for the location. This is because multiple demands of one type can exist for one location. The different types have different complexity: Electricity demand does not need any further specification, heat and gas demand need a specified temperature or pressure level, respectively. Further, energy from electricity and the gaseous carriers is just consumed, heat demands have a returning energy flow.
2.6 Helpers

Besides the part of the energy system, MTRESS offers some helpers to facilitate working with the models.

Reproducible runs  It is possible to create an energy system model using the Python API and to export it to a YAML file afterwards. This way, models created dynamically using the Python API can be easily checked and results can be reproduced without running the full program again.

Analysis of the results  Energy flows in MTRESS are categorised using tags. It is possible to filter for these tags, e.g. to sum up heat coming from heat pumps in several buildings. Further analysis and plotting can be done by exporting results to Pandas [15].

Energy system graph plotting  For quick checks and for understanding the layout, we implemented a simple graph plotting routine. It displays every node of the final energy system graph and the connections between those. Trape-zoid shapes signify sources (smaller side up) or sinks (smaller size down), cycles signify busses and octagonal shapes signify more complicated energy converters. Adding to the same functionality in solph, the MTRESS plotter groups these nodes corresponding to the location and further according energy carrier, component, or demand they belong. An example is displayed in Fig. 2. For a later publication, the plotted graphs can be exported as graphml and edited manually in graph visualisation tools.

3 Linearized Formulation of Energy Storage

For the gas storage, available pressure depends on the storage content. The latter, however, is an optimisation variable. The same argument is valid for a (sensible) heat storage when it comes to the temperature of the medium that can be taken from the storage. Thus, linear formulation of such storage types is not trivial. As discussed in Sec. 2.3 we implement an approach that uses discrete levels. Using the example of a gas storage, it has varying pressure that defines the content of the storage, i.e.

\[ E(t) = c_E \cdot p(t), \]

where \( E \) denotes the energy content of the storage at time \( t \), \( p \) the pressure inside the storage at time \( t \) and \( c_E \) is a storage specific constant depending on the energy density of the gas and the volume of the storage. Following the definition of the \texttt{EnergyCarrier}, the pressure is discretized

\[ p_n, \ n \in \{1, \ldots, N\}, \]

and \( E_n := c_E \cdot p_n \) denote the energy contents of the storage at the defined pressure levels.
Now, we want that an active (or usable) level is signified by the binary status variable \( y_n(t) \in \{0, 1\} \) with

\[
\begin{align*}
y_n(t) &= 0 \text{ if } E(t) < E_n, \quad \text{(3a)} \\
y_n(t) &= 1 \text{ if } E(t) \geq E_n. \quad \text{(3b)}
\end{align*}
\]

Note that \( E \) is being optimised, so Eq. (3) cannot be read as a causal relation. We also need a linear formulation. We suggest

\[
\begin{align*}
y_n(t) &\leq \frac{E(t)}{E_n}, \quad \text{(4a)} \\
\bar{y}_n(t) &\geq \frac{E(t) - E_n}{E_{\max}}, \quad \text{(4b)} \\
\bar{y}_n(t) &= 1 - \bar{y}_n(t), \quad \text{(4c)}
\end{align*}
\]

where \( E_{\max} \) is the maximum storage content. Equation (4a) guarantees Eq. (3a) but relaxes Eq. (3b) in the sense that \( y_n \) is not forced to be active. To compensate for that, Eq. (4c) enforces \( \bar{y}_n = 0 \) for the given case. The symbol is chosen to emphasise that it can be read as an inverse status. If this should be strictly the case, also

\[
1 = y_n(t) + \bar{y}_n(t) \quad \text{(4d)}
\]

has to be defined to eliminate the possibility that \( y_n(t) = \bar{y}_n(t) \), i.e. at \( E = E_n \), where both can be 1.

Now, note that gas leaving the storage needs to have lower pressure than the storage and higher pressure is needed to increase the storage content. Thus,

\[
\begin{align*}
P_{\text{out},n}(t) &\leq y_n(t) \cdot P_{\text{out},\max,n}, \quad \text{(5a)} \\
P_{\text{in},n}(t) &\leq \bar{y}_n(t) \cdot P_{\text{in},\max,n}, \quad \text{(5b)}
\end{align*}
\]

where \( P_{\text{out},n} \) and \( P_{\text{in},n} \) denote the power flow out of and into the storage, respectively, at the pressure \( p_n \). \( P_{\text{out},\max,n} \) and \( P_{\text{in},\max,n} \) are the absolute limits of these flows. This way, it is guaranteed that \( P_{\text{out}}(t) = 0 \) if the storage content is not sufficient and \( P_{\text{in}}(t) = 0 \) if the storage content is too high.

So, at each point in time, the storage content \( E \) defines the pressure \( p \) in the storage and thus limits the withdrawal pressure or the feed pressure. As multiple output and input flows can be active at the same time, it is meaningful to also define a weighted limit

\[
\sum_n P_{\text{out},n}(t) \cdot w(p_n) \leq P_{\text{out},\max}, \quad \text{(6)}
\]

so that the total power flow out of the storage, and analogously for the input flows, is also constrained.

A further complication comes up due to discrete time steps. A naive implementation might allow to pass a pressure level \( p_n \) within one time step using \( P_{\text{out},n}(t) > 0 \) – even a full storage can be completely emptied using the highest
Figure 1: Working principle of the status variable $y_n$: If the stored energy exceeds the limit (at the end of a time step), the corresponding level might be active.

pressure level. If either power limits as in Eq. (5) are set low or the time resolution is high, this will not impose a problem. However, there is a solution that explicitly solves the issue.

$$P_{\text{out},n,t} \leq y_{n,t} \cdot P_{\text{out,max},n},$$  \hspace{1cm} (7a)  
$$P_{\text{in},n,t} \leq \overline{y}_{n,t} \cdot P_{\text{in,max},n},$$  \hspace{1cm} (7b)

is a time-discrete reformulation of Eq. (5), where the index $t$ denotes the time interval between $t$ and $t + \Delta t$. If now the constraint for the status variable is defined by the energy content at the end of that time interval

$$y_{n,t} \leq \frac{E_{t + \Delta t}}{E_n},$$  \hspace{1cm} (8)

it is no longer possible to cross a level $p_n$ using the corresponding power flows. For a storage with levels at $E_n = [0, 0.3, 0.6, 0.9, 1] \cdot E_{\text{max}}$, the principle is depicted in Fig. 1. Lines for the highest and the lowest level are omitted because they are always active or inactive, respectively. This implies that at any time the lowest level cannot be used for storing energy and energy at the highest level cannot be obtained from the storage. For a fully mixed heat storage, this implication can be read as the fact that a storage will never reach (exactly) the temperature that is used to feed it.

Generally, however, inside a heat storage stratification is possible. Thus, a second heat storage model is offered [11], that works without binary variables. It models different temperature layers of variable height that share the same volume. We assume that the warmest temperatures are at the top and temperature decreases until the bottom of the storage tank. This way, multiple temperatures can be served at the same time using the same storage.

For electricity, the presented method can be used to implement charging-rates that depend on the state of charge.
4 Example

Figure 2: Example energy system graph as plotted by the automatic plotting routine.

The case of a single-family home using a heat pump for heat supply will serve as a basic example. First of all, the `EnergySystem` object has to be created. As stated above, it will nest the locations and contains global information about the problem. The simplest way to define the time horizon of the optimisation is by handing the needed information as a dictionary:

```python
energy_system = EnergySystem(time_index=
    "start": "2021-07-10 06:00:00",
    "end": "2021-07-10 08:00:00",
    "freq": "60T",
})
```

Note that the boundaries given above define two time intervals. Next, we create an empty location. As there can be many locations, the location has to be given a unique name as an identifier.
We add the location to the model at this point, just to have it done. Generally speaking, the order of the individual steps of creating the model is not important for the result. In particular, it is also possible to create and populate the locations first, before creating the EnergySystem object.

By giving a working price, it is implied that energy for that carrier can be purchased (from an external grid). The convention for the units is not binding, e.g. using € MW$^{-1}$ and MW would also be possible, as long as it is consistently done for all carriers and demands. As for all demands, the electricity demand time series is given in units of power. The energy system defined up to this point describes a complete electricity-only energy system and could be used as such.

For the heat sector, temperature levels and a reference temperature have to be defined. The reference temperature has to be lower than or equal to the lowest return temperature. Besides, every temperature required by the demands has to be defined as a level for the carrier.
house.add_demand(
    demands.FixedTemperatureHeat(
        name="hot water",
        flow_temperature=55,  # °C
        return_temperature=10,  # °C
        time_series=[0, 12],  # kW
    )
)

Note that we did not define costs for the heat carrier, an equivalent expression would be costs=None. Defining it would be interpreted as a connection to the heating grid, i.e. setting it to zero would make it free. So, we need an energy conversion technology. In our example, an air-source heat-pump is used. It consists of two individual components, the actual HeatPump and the corresponding anergy source:
	house.add_component(
    technologies.HeatPump(
        thermal_power_limit=None
        cop_0_35=3.8,  # 1
    )
)
	house.add_component(
    technologies.AirHeatExchanger(
        air_temperature=[3, 9],  # °C
    )
)

In Figure 2 the resulting energy system is displayed as a graph. This graph was automatically generated by MTRESS building upon using graphviz [16]. Once defined, the model is optimised using:

energy_system.optimise()

Afterwards, results can be prompted

electricity_flows = energy_system.flows(Carrier, Electricity)

The alternative is to define the energy system using a yaml file. The following listing will result in exactly the same model as the code explained above:

general:

    timeindex:
        start: 2021-07-10 06:00:00
        end: 2021-07-10 08:00:00
        freq: 60T

    locations:
SFH:

carriers:
  Heat:
    temperature_levels:
      - 20. °C
      - 30. °C
      - 55. °C
    reference_temperature: 10 °C

Electricity:
  demand_rate: 0 # ct/kW
  working_price: 35 # ct/kWh

demands:

  Electricity:
    name: "electricity demand"
    time_series: [7, 8.4] # kW

FixedTemperatureHeat:
  name: "space heating"
  time_series:
    - 13.37 # kW
    - 42 # kW
  flow_temperature: 30 °C
  return_temperature: 20 °C

FixedTemperatureHeat:
  name: "hot water"
  time_series:
    - 0 # kW
    - 12 # kW
  flow_temperature: 55 °C
  return_temperature: 10 °C

components:

  AirHeatExchanger:
    parameters:
      air_temperature: [3, 9] °C

  HeatPump:
    parameters:
      cop_0_35: 3.8

Note that all comments are voluntary and are just meant to help the reader. For longer time series, it can be convenient not to inline every value. This is supported by giving it in the form:

```
  air_temperature: file=weather.csv:temperature (°C)
```

which denotes that the time series can be found in the column “temperature (°C)” of the file “weather.csv”. Time series used in models can be either defined
at points in time or over time intervals. For time-intervals, MTRESS uses left-indexed data, meaning that the time stamp denotes the beginning of the interval the value is valid. Following the convention of solph this is being made explicit by adding the time step limiting the last interval with “NaN” (for “not a number”) instead of data. It might sound a bit pedantic at first, but giving the length of the last interval is actually required because there is no requirement that all time intervals have the same length. Additionally, being explicit helps avoiding common off-by-one errors.

5 Summary and Outlook

We presented version 3.0 of MTRESS, a tool that allows to create optimisation models for residential energy supply systems in just a few lines of code. These models can contain multiple temperature levels for the energy carrier heat and multiple pressure levels for gases (like natural gas or hydrogen) in a transparent and flexible way. This way i.e. storage capacities can be modelled more realistically compared to traditional linear models without levels. There are two ways to create those models, on one hand, there is a Python API for dynamic modelling, on the other hand a YAML interface is provided. For the future, it is planned to allow exporting models as YAML files to facilitate reproducing results of energy system designs that were created using a dynamic algorithm.

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