

HOW TO GUIDE

**Modelling multiple temperatures and  
internal heat sources in energyPRO**



**energy** PRO



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### **About energyPRO**

**energyPRO is a Windows-based modeling software package for combined techno-economic analysis and optimisation of complex energy projects with a combined supply of electricity and thermal energy from multiple different energy producing units.**

**The unique programming in energyPRO optimises the operations of the plant including energy storage (heat, fuel, cold and electrical storages) against technical and financial parameters to provide a detailed specification for the provision of the defined energy demands, including heating, cooling and electricity use.**

**energyPRO also provides the user with a detailed financial plan in a standard format approved by international banks and funding institutions. The software enables the user to calculate and produce a report of the emissions by the proposed project.**

**energyPRO is very user-friendly and is the most advanced and flexible software package for making a combined technical and economic analysis of multi-dimensional energy projects.**

**For further information concerning the applications of energyPRO please visit [www.emd.dk](http://www.emd.dk).**

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# Contents

In this How To Guide, you will learn how to build an energyPRO model with multiple temperatures and with utilization of internal heat sources at a district heating plant. The first chapters explain the concept and relevance of the model as well as the calculation methodology. The last chapters explain how to build, use, and modify the model.

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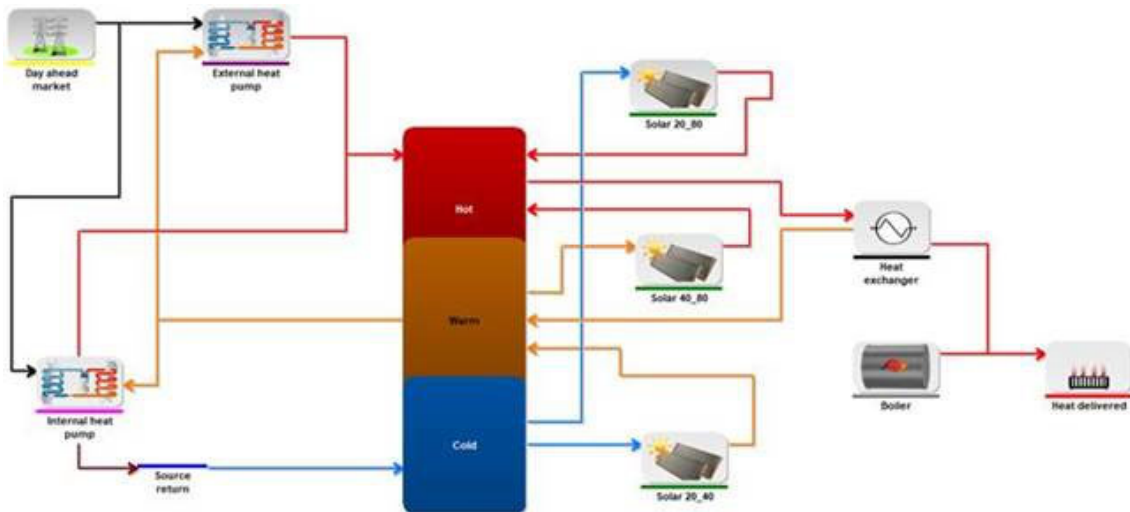
# Introduction

In the transition to renewable energy, the efficiency of many of the energy conversion units applied at district heating plants rely heavily on the temperatures in the system. Energy conversion units such as solar collectors are an example of this, where decreasing the inlet and outlet temperatures allow significantly higher thermal production as well as production during periods, where it would normally not be possible to harvest much energy from the sun.

Many district heating plants have installed or are installing large heat pumps in the transition to renewable energy. Such heat pumps are normally operated using an external heat source such as ambient air or sea water, which is cooled to heat the district heating return water. However, the cooling effect of the heat pump can also be utilized to increase the efficiency of for example solar collectors. This is done by simultaneously cooling part of the district heating return water and heating part of the return water. In other words, the heat source is internal rather than external. This type of operation is simply moving energy from one part in the system to another, where the only energy that enters the system is the electricity consumed by the compressor.

It is as an example desired to be able to model, whether the value on the increase in thermal production on the solar collectors, due to lower inlet and outlet temperatures, can outweigh the opportunity cost of not operating the heat pump with an external heat source in some hours - as well as the cost of electricity for operating the heat pump with an internal heat source.

This requires a model with multiple temperature levels in the thermal storage as well as a model, where the energy conversion units heat water to different temperatures. This is currently not supported with the built-in features of energyPRO and has thus not been possible to model.



However, using the newly added MILP solver in energyPRO, it is possible to make such a model. This How To Guide describes how to create and solve such a model in energyPRO, which allows the user to analyze whether operating a heat pump with internal heat sources is feasible during some hours of the years. If this is

true, it allows the district heating plant to lower their operation costs with little to no new investments.

## Calculation methodology

To do calculations on energy systems with water at multiple temperature levels, the flow of water is modelled rather than the flow of energy. However, the model needs to be able to accept a mixture of both flow of water and flow of energy, such that a heat demand for example can be specified in MWh, while the content of the storage tank can be specified in m<sup>3</sup>. For this purpose, conversion factors between volume and energy need to be defined. The following methodology takes departure in an energy system with three temperature levels, but the same concept applies to models with additional temperature levels.

The three temperatures in the energy system are defined by the constants:

- $T_{hot}$
- $T_{warm}$
- $T_{cold}$

The energy required to heat 1 m<sup>3</sup> of water from  $T_{cold}$  to  $T_{hot}$  is then calculated as:

$$E_{hot} = c_p \cdot (T_{hot} - T_{cold}) \cdot m$$

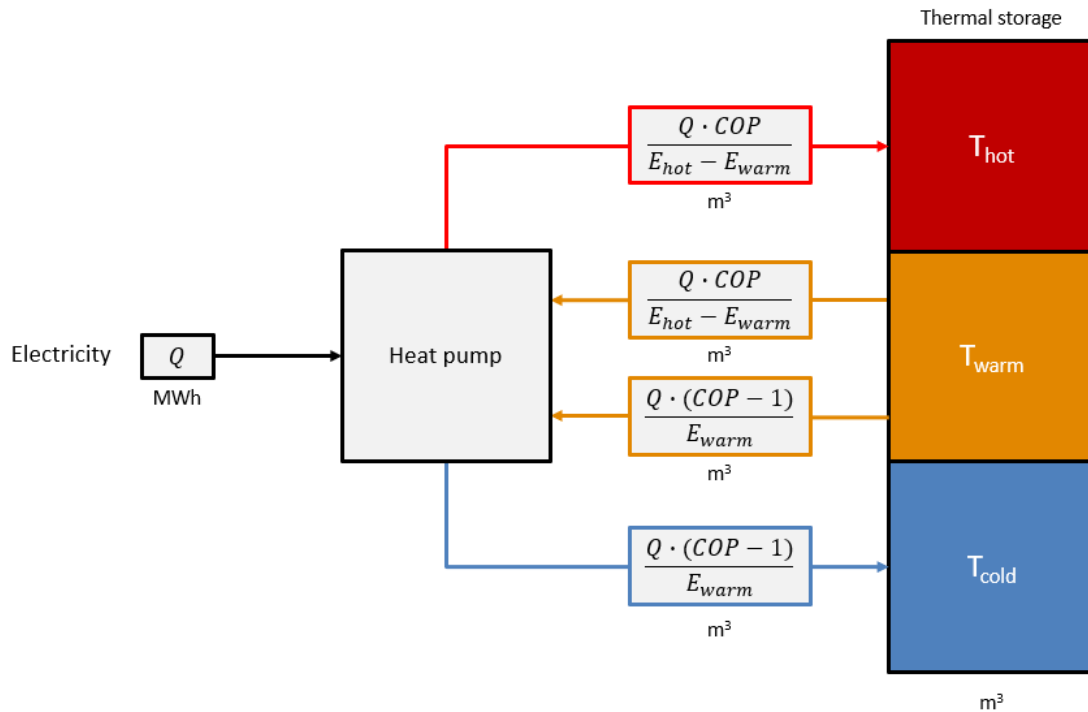
where  $c_p$  is the specific heat capacity of water and  $m$  is the mass of 1 m<sup>3</sup> of water. Choose the corresponding units in the calculation, such that the constant converts to the desired energy unit, for example MWh. In the same manner, the energy required to heat 1 m<sup>3</sup> of water from  $T_{cold}$  to  $T_{warm}$  is then calculated as:

$$E_{warm} = c_p \cdot (T_{warm} - T_{cold}) \cdot m$$

For an energy system with three temperature levels, only these two constants are needed, as the energy required to heat 1 m<sup>3</sup> of water from  $T_{warm}$  to  $T_{hot}$  can then be calculated as:

$$E_{hot} - E_{warm}$$

It is now possible to model a heat pump utilizing internal heat sources. This heat pump simultaneously uses the water at  $T_{warm}$  as both the heat source and heat sink. Given an electric capacity,  $Q$ , and a coefficient of performance,  $COP$ , the flow of water can be calculated as shown in the figure below:



**Figure 1**

A model of a heat pump utilizing internal heat sources. The three regions of the storage are measured in  $\text{m}^3$ , as well as the flows of water in and out of the heat pump at different temperatures. However, the electricity consumed by the heat pump is defined in MWh or another desired energy unit.

Using this approach, the total volume of the thermal storage always remains the same, as equal volumes of water are removed and inserted in the storage across the different temperature regions. This is valid under the assumption, that the specific heat capacity of the fluid remains constant.

Most likely, the demand for heat to be delivered to the district heating grid is measured in energy units such as MWh. In an energy system where the forward temperature is equal to  $T_{hot}$  and the return temperature is equal to  $T_{warm}$ , the volumes of water can be converted back into energy units, using the same constants as before. Removing  $1 \text{ m}^3$  water at  $T_{hot}$  and delivering it back at  $T_{warm}$  is the same as consuming an amount of energy equal to  $(E_{hot} - E_{warm})$ .

Using this calculation methodology, all sorts of energy conversion units can be introduced to the model, such as boilers with flue gas condensation and solar collectors operating at different temperature levels depending on solar irradiation.

It is possible to optimize the operation of these energy systems in energyPRO using the MILP calculation method only.



## Modelling procedure

Open a new and empty energyPRO project. The first step of the modelling procedure is to set the calculation module to "OPERATION". Go to "Project setup" → "Project identification" and click the radio button.

Next, go to "Advanced settings" and toggle the checkbox "Fuel producing energy units in project". While you are here, also check "Delivery of both heat and process heat" but uncheck "Process Heat" further down.

## Thermal storage and heat pump

First, we define the desired parameters. These are added in energyPRO as time series functions. Define the following constants, using the calculation methodology previously explained:

- $T_{\text{hot}}$  [°C]
- $T_{\text{warm}}$  [°C]
- $T_{\text{cold}}$  [°C]
- $E_{\text{hot}}$  [MWh/m<sup>3</sup>]
- $E_{\text{warm}}$  [MWh/m<sup>3</sup>]

Furthermore, add the following constants, specifying the parameters of the heat pump.

- Electric capacity of heat pump [MW-e]
- Internal COP
- External COP

The COP does not necessarily have to be a constant. It can also be a function depending on for example varying external temperature conditions.

Now, to model fluids in energyPRO, the water at each temperature level is added as a fuel, as shown in the figure below.



To model a heat pump that can operate with both external and internal heat sources, we are going to add two energy conversion units. Both energy conversion units should be a "User Defined Unit".

We start by modelling the external operation mode of the heat pump. Open the properties of one of the user defined units and set the "Fuel input" to the warm

water and the "Fuel output" to the hot water. Enable the checkbox "Enable formulas in power curve" and specify the "Fuel input" and "Fuel output" formulas as following:

$$HP\_cap(\_) * COP\_external(\_) / (E\_hot(\_) - E\_warm(\_))$$

Here, the variable  $HP\_cap(\_)$  refers to the electric capacity of the heat pump. In the field "Elec. consump." enter the formula:

$$HP\_cap(\_)$$

Go to the "Operational" tab and check "Partial load allowed" and "Operation dependent on other unit". Choose that the operation is only allowed when no production is occurring on the other heat pump. In this manner, the heat pumps are modelled as the same physical unit with two distinct operation modes.

Next, we model the internal operation mode of the heat pump. Open the properties of the other user defined unit and set "Fuel input" to the warm water and the "Fuel output" to the hot water again. Apply the same settings as before under "Operational". In the power curve field for "Fuel input" enter the following formula:

$$HP\_cap(\_) * COP\_internal(\_) / (E\_hot(\_) - E\_warm(\_)) \\ + HP\_cap(\_) * (COP\_internal(\_) - 1) / (E\_warm(\_))$$

In the "Fuel output" field enter the following:

$$HP\_cap(\_) * COP\_internal(\_) / (E\_hot(\_) - E\_warm(\_))$$

In the "Process Heat" field enter the following:

$$HP\_cap(\_) * (COP\_internal(\_) - 1) / (E\_warm(\_))$$

In the "Elec. consump." field enter the following:

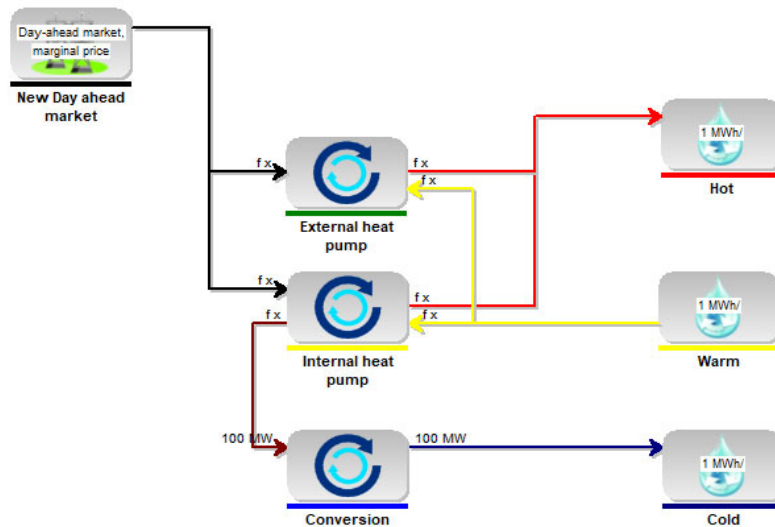
$$HP\_cap(\_)$$

For the heat pumps to work, add a time series for the electricity price and then add a new electricity market to the model.

Then add a new "User Defined Unit". Set the "Fuel output" to the cold water and set the power curve field "Proc. Heat Consump." to an arbitrary high value, say 1000 MW, and the "Fuel Output" field to the exact same value. Go to "Operational" and allow partial load. This unit allows the internal heat pump to produce a second fuel, namely the cold water.

Lastly, open the properties of each fuel and check "Restrictions and storage". Set the "Fuel storage, max utilizable content" to the same value in each fuel. This value should be the capacity of the thermal storage in  $m^3$ . For the warm water specifically, set the "Fuel store content at" and the "Fuel store content desired at" equal to the thermal storage utilizable content. In this manner, the thermal storage starts filled with water at the temperature  $T_{warm}$ .

The model should now look like this:



## Solar collectors

We cannot use the built-in energy conversion unit for solar collectors, as this unit is currently only capable of producing heat. We need the solar collectors to produce water at different temperatures, which we have defined as fuels.

The procedure is therefore to create a new energyPRO model. In this model we add the built-in Flat Plate Solar Collectors with the desired properties. Use the correct temperatures, corresponding to either  $T_{hot}$ ,  $T_{warm}$  or  $T_{cold}$ . Next, we add an enormous thermal storage tank, gas boiler and an extremely high demand for heat. We make sure to add an arbitrary cost for operating the gas boiler. We then calculate the model and export the thermal production of the solar collectors using "Tools" → "Export Energy Conversion". Make sure to select the desired resolution.

Paste the export into Excel and find the column for the thermal production of the solar collectors. Then add this column as a time series in the original energyPRO

model, containing the three temperature levels. Give the time series a symbol with the format, SC\_X\_Y, where X and Y are the inlet and outlet temperatures of the collectors, respectively. Repeat this procedure for all the temperatures, that the solar collectors should work with:

- $T_{\text{cold}} \rightarrow T_{\text{warm}}$
- $T_{\text{cold}} \rightarrow T_{\text{hot}}$
- $T_{\text{warm}} \rightarrow T_{\text{hot}}$

We now have three time series in our original model, one for each operation mode of the solar collectors. Now, add three user defined units to the model. In their properties under "Operational", make sure that they cannot operate at the same time, in the same manner as we did with the heat pumps.

For each unit, select the appropriate "Fuel input" and "Fuel output" and enter the corresponding formula in the power curve fields for both "Fuel input" and "Fuel output":

$$SC_{\text{cold\_warm}}(\_) / E_{\text{warm}}(\_)$$

or

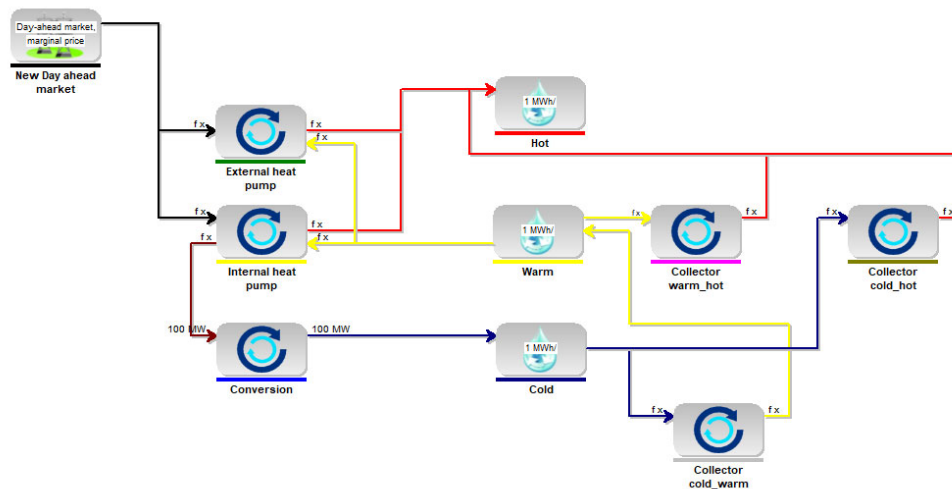
$$SC_{\text{cold\_hot}}(\_) / E_{\text{hot}}(\_)$$

or

$$SC_{\text{warm\_hot}}(\_) / (E_{\text{hot}}(\_) - E_{\text{warm}}(\_))$$

At last, go to the properties of every unit conversion unit in the model, and enable "Allow production to store" under "Operational", as we now have multiple units that can produce to the same storage. Remember to also do this for the heat pumps.

The model should now look like this:



## Woodchip boiler with a condenser

First, we specify the parameters of the woodchip boiler. Add the following constants as time series functions:

- Woodchip boiler thermal capacity [MW-heat]
- Condenser efficiency

The condenser efficiency should be interpreted as the added efficiency of the woodchip boiler by cooling the flue gas with  $T_{\text{cold}}$  rather than  $T_{\text{warm}}$ . For example, if the woodchip boiler has a thermal capacity of 10,0 MW-heat and using  $T_{\text{cold}}$  instead of  $T_{\text{warm}}$  allows for a thermal capacity of 10,4 MW-heat, the condenser efficiency is set to  $10,4 / 10,0 - 1 = 0,04$ .

Next, we add two user defined units. One of them is the actual woodchip boiler. We do not allow this unit to partial load, but we allow it to produce to store under "Operational". As "Fuel input" we select warm water and as "Fuel output" we select hot water. In the power curve fields we enter the following for both "Fuel input" and "Fuel output":

$$B\_cap(\_) / (E\_hot(\_) - E\_warm(\_))$$

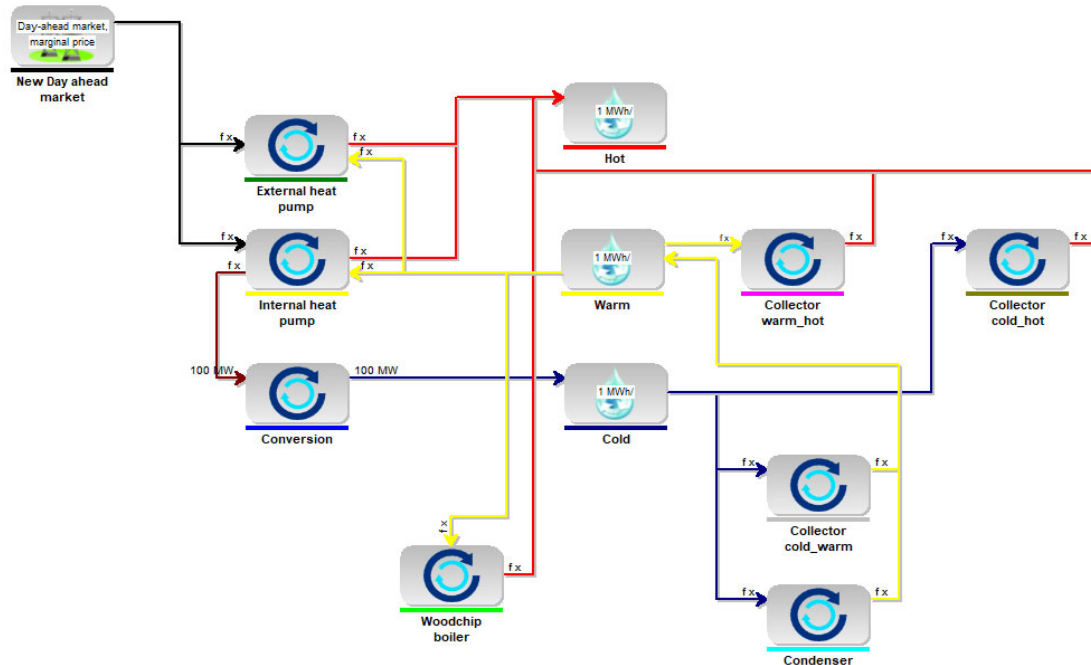
Here,  $B\_cap$ , is the thermal capacity of the woodchip boiler.

We now modify the second user defined unit, that we created. We allow this one to partial load under "Operational", but we only allow it to produce when the woodchip boiler is being operated. As "Input fuel" we select cold and as "Output fuel" we select warm. Enter the following in the power curve fields for both "Fuel input" and "Fuel output":

$$B\_cap(\_) * c\_eff / E\_warm(\_)$$

Here,  $c\_eff$ , is the efficiency of the condenser.

The model should now look like this:

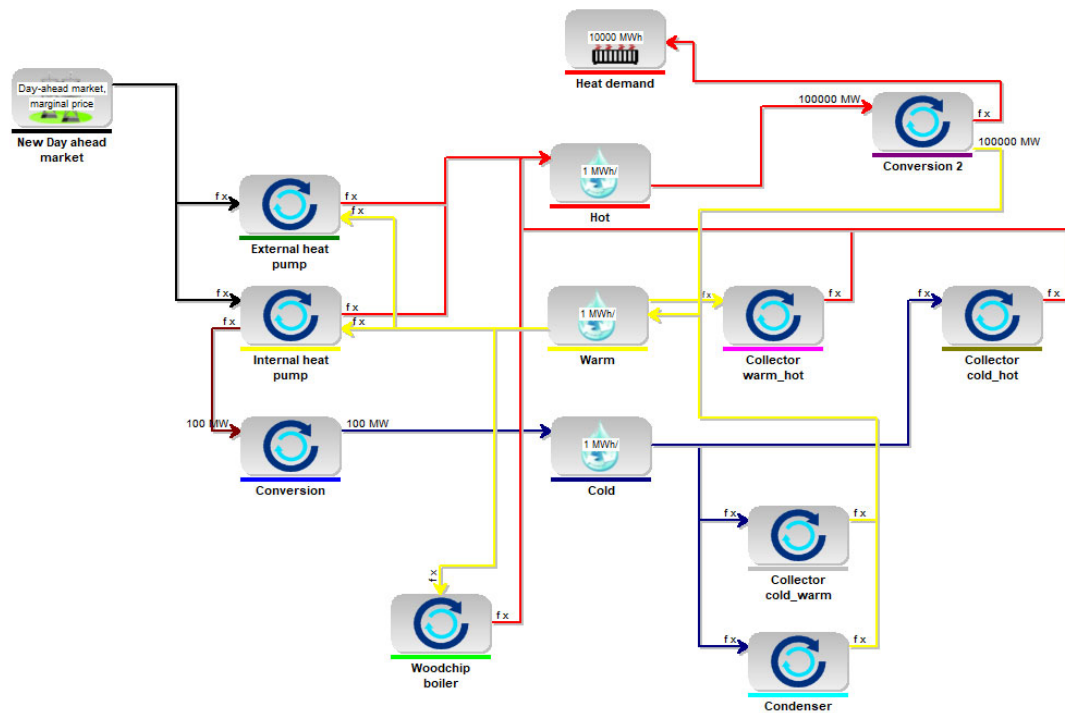


## Heat demand

As the last thing, we need to add a heat demand. We simply use the built-in function to add a heat demand and define the properties as we desire. Then we add a new user defined unit for converting the m<sup>3</sup> of water into energy units.

Set the "Fuel input" as hot water and the "Fuel output" as warm water. In the power curve, set an enormous value for the "Fuel input" and set the exact same value as the "Fuel output". For the power curve value of "Heat" multiply this enormous value with  $(E_{hot}(\_) - E_{warm}(\_))$  to convert back into MWh or your specified energy unit. Under "Operational", allow production to store as well as partial load.

This gives us the final model, which can model the usage of internal heat sources in combination with both a woodchip boiler and solar collectors. The model should look like this, although there is room for visual improvements by aligning the units better and changing the icons:



## Optimizing the operation and getting the results

It is not possible to use the “Analytical” solver to optimize the operation of the model. To run the model, click on “Analytical” in the top menu. Change the “Type of Solver” to MILP. Set the “Max. solution time” to 600 and the “Wanted precision” to 1%. It is a complicated model, so these settings allow enough leeway and computation time to find an optimal operation.

Unfortunately, the built-in graphs in energyPRO are not capable of presenting the results of the model on their own. Instead, export the results using “Tools” → “Export Energy Conversion”. Paste the results into Excel. Keep in mind that most of the units are in  $m^3$  of water and not in MWh, although the header row says so! Convert them back into MWh manually, using the values of the constants  $E_{hot}$  and  $E_{warm}$ .

## Modifying the model

It is possible to scale and modify the model explained in the previous section. This section covers some of these modifications.

### Adding built-in units to the model

It is possible to add built-in units to the model, such as an electric boiler for covering peak demand. However, built-in units cannot produce to the thermal storage with three temperature levels. Built-in units are also assumed to heat water from  $T_{\text{warm}}$  to  $T_{\text{hot}}$ , where  $T_{\text{warm}}$  is equal to the district heating grid return temperature, and  $T_{\text{hot}}$  is equal to the forward temperature. If these conditions are not true, the built-in unit should instead be modelled as another user defined unit, calculating with volume of water instead of energy.

### Changing the temperatures

The temperatures can be changed by modifying the constants in the time series functions. However, keep in mind that changing the temperatures requires you to recalculate the solar collector time series as well with these new temperatures if the model contains solar collectors.

### Changing the thermal storage capacity

When changing the thermal storage capacity, make sure that the change is reflected in each region of the three-temperature thermal storage and that the initial and final values of the storage reflect the changes. The "Fuel storage, max utilizable content" should be the same value for each region of the thermal storage, and the sum of "Fuel store content at" as well as the sum of "Fuel store content desired at" across all temperature regions should also be equal to this same value.

### Relating the COP to a variable external condition

In the time series function defining the COP, one can enter an arbitrary function that relies on external conditions. The following code implements the COP estimation method used in the built-in heat pump unit in energyPRO for the internal operation mode of the heat pump:

$$\frac{((\text{HotTemp}(\_) - \text{WarmTemp}(\_)) / \log((\text{HotTemp}(\_) + 273.15) / (\text{WarmTemp}(\_) + 273.15)))}{((\text{HotTemp}(\_) - \text{WarmTemp}(\_)) / \log((\text{HotTemp}(\_) + 273.15) / (\text{WarmTemp}(\_) + 273.15))) - ((\text{WarmTemp}(\_) - (\text{ColdTemp}(\_))) / \log((\text{WarmTemp}(\_) + 273.15) / ((\text{ColdTemp}(\_) + 273.15))))} * \text{HPn}(\_)$$

Here,  $\text{HPn}(\_)$ , denotes the constant Lorentz-efficiency, typically around 0.5. For the external operation mode of the heat pump, use the following formula:

$$\frac{((\text{HotTemp}(\_) - \text{WarmTemp}(\_)) / \log((\text{HotTemp}(\_) + 273.15) / (\text{WarmTemp}(\_) + 273.15)))}{((\text{HotTemp}(\_) - \text{WarmTemp}(\_)) / \log((\text{HotTemp}(\_) + 273.15) / (\text{WarmTemp}(\_) + 273.15))) - ((\text{T}(\_) - (\text{T}(\_) - \text{EHQ}(\_))) / \log((\text{T}(\_) + 273.15) / ((\text{T}(\_) - \text{EHQ}(\_) + 273.15))))} * \text{HPn}(\_)$$

Here,  $\text{EHQ}(\_)$ , denotes the cooling of the external heat source in K, and  $\text{T}(\_)$  denotes the temperature of the external heat source.



Please notice, that you can find more information on how to use energyPRO in the How to Guides, User's Guide and tutorials on EMD's website:  
<http://www.emd.dk/energypro/>

