Two Steady State CHP Models with Modelica : Mirafiori overall Model and Multi-configuration Biomass Model

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Abstract

Steady state 0D/1D models are useful to check, validate and improve through simulation the energy performances of existing heat and/or power plants. They are also used to find the best design that meets required economical criteria.
A library of fully static 0D thermal-hydraulics component models was built. It contains the models of a grid furnace, gas combustion chamber, electrical boiler, steam boiler, multifunctional heater, waterwall gas/water steam exchangers, tubular air heater, steam turbine, condenser, aero-condenser, pump, drum, valves, pipes, gas turbine, compressor, kettle boiler, mixer and splitter etc...
This library now enables us to build models of any CHP plant. A 0D steady state model of the MiraFiori heat and power plant was built in order to check, validate and improve the energy performances of the plant. A multi configurations steady state model of a combined heat and power biomass plant was built, the plant satisfies the steam demand during all the year and produces electricity with its remaining energy.
Models were built by connecting the component models in a technological way, so that its topology reflects the process flow diagram of the plant.

A preliminary calibration of the Mirafiori model was made based on measurement data obtained from on-site sensors and using inverse calculations. The best steam cycle configuration for the Biomass CHP plant was chosen computing various normal conditions points. The models were then able to compute precisely the distribution of the steam/water mass flow rates, pressure and temperature across the network, the exchangers thermal power, and the performance parameters of all the equipments. They converge very quickly, provided that the iteration variables are properly fed in by the user (approx. 5% of the total number of variables).

1 Introduction

Modelling and simulation play a key role in the design phase and performance optimization of complex energy processes.

Steady state 0D/1D models are useful to check, validate and improve through simulation the energy performances of existing heat and/or power plants. They are also used to find the best design that meets required economical criteria.
The modelling and simulation of the plant was originally carried out with LEDA. LEDA is a tool developed and maintained by EDF since 1982 for the modelling and simulation of the normal or incidental operation of nuclear and conventional thermal plants.

For present and future models, we are using MODELICA modelling tool. New blocks and models are being developed with Modelica and standard guidelines have been adopted for power plants modelling. It is now used at EDF-R&D as well as in Engineering Departments.
Modelica models are used by EDF to improve its knowledge about existing or future types of power plants, check the design performances and understand important transients situations.

Besides technical benefits of Modelica, it is likely that using a free and non proprietary language will promote partnerships around joint R&D and engineering projects, thus giving the opportunities to share development costs between participants.

Two Steady State CHP models with Modelica - Mirafiori overall model and Multi-configuration Biomass model - were built in 2007.
The modelling and simulation were carried out with the commercial tool Dymola, as it is the most advanced Modelica based tool up to now.

2 Modelling practices at EDF

Modelling and simulation play a key role in the design phase and performance optimization of complex energy processes. At EDF, modelling and simulation of the plant was originally carried out with LEDA. LEDA is a tool developed and maintained by EDF for the modelling and simulation of normal or incidental operation in nuclear and fossil-fuel power plants. LEDA models are used by researchers and engineers in order to improve their knowledge of existing or future types of power plants, to check the design performances and to understand important transient situations.

EDF traditionally used steady state models in order to check precisely the performances and the design given by manufacturers. EDF used dynamic models to check automation and operating procedures and to optimise design for a specific operation.

In order to improve the performance of its simulation tools while reducing their cost, EDF R&D made the decision to replace LEDA with Modelica and the commercial tool Dymola.

Application fields

- Nuclear power plants.
- Thermal fossil fuel fired power plants (pulverized coal, fluidized bed, ...).
- Combined heat and power plants.
- Waste to energy.

Utilization fields

- Operation and maintenance.
- Design and analysis.
- Innovative technologies.

3 EDF Modelica Library

3.1 Component models

A library of fully static 0D thermal-hydraulics component models was built. It contains the models of a grid furnace, gas combustion chamber, boiler, electrical boiler, steam boiler, multifunctional heater, waterwall gas/water steam exchangers, tubular air heater, steam turbine, condenser, aero-condenser, pump, drum, valves, pipes, gas turbine, compressor, kettle boiler, mixer and splitter etc...

The model equations take into account the non-linear and the state-of-the-art physical behaviour of each important phenomenon.

3.2 The thermodynamic properties

Properties of flue gases

The thermo-physical properties of the flue gases (for the exchangers, gas turbines, compressors, gas combustions chambers, …..) were computed using Fortran subroutines called MONOMELD.

Properties of water and steam

The properties for water and steam were computed from polynomials defined by the international standard IAPWS-IF97. The efficient original Modelica implementation of H. Tummescheit was used.

4 The Mirafiori model

Steady state model of the MiraFiori heat and power plant was built in order to check, validate and improve the energy performances of the plant. The model contains six units (systems) of production :

- HP water/steam cycles with 3 gas boiler,
- IP water/steam cycles with 4 gas boiler,
- 2 combined cycles,
- 2 GT.

As it has already been mentioned, MiraFiori is a fully static model.

The full model is built by connecting the component models in a technological way, so that its topology reflects the functional schema of the plant (see Figure 7 in the appendix). It is composed of 420 elementary models, generating 9560 variables and 1950 non-trivial equations.

The model is composed of : 7 gas boilers,14 exchangers, 10 steam turbine stages, 15 pumps, 28 pressure drops, 4 gas turbines, 4 compressors, 4 kettles boilers, 4 gas combustions chambers, several mixers, several collectors and several boundary conditions.

It is very important to provide an efficient way to handle the iteration variables, as the task of setting them properly is time consuming. It is by no way automatic, since it requires a good expertise of the problem to be solved (the number of iteration variables represent roughly 5% of the total number of variables).

4.1 Model calibration

The calibration phase consists in setting the maximum number of thermodynamic variables to known measurement values (enthalpy, pressure, mass flow rates), taken from on-site sensors during performance tests. This method ensures that all needed performance parameters, size characteristics and output data can be computed.

A preliminary calibration of the model was made based on measurement data obtained from on-site sensors. The model was then able to compute precisely the distribution of water and steam mass flow rates, pressure and temperature across the network, the exchangers thermal power, and the performance parameters of all the equipments. It converges very quickly, provided that the iteration variables (approx. 5 % of the total number of variables) are properly fed in by the user.

The main computed performance parameters are :

- the ellipse law coefficients of the turbines,
- the isentropic efficiencies of the turbines,
- the pressure drop correction coefficients of the exchangers and of the pipes between pieces of equipment.
- the compression ratio of the GTs.

Etc.

The main computed outputs are :

- fuel mass flow rate of gas boilers,
- Air mass flow rate of gas boilers,
- thermal power of exchangers,
- temperatures and pressures in places where no sensor are installed.

Etc.

4.2 Simulation results

After calibration, the model allowed us to make what-if simulation and provide to the plant operators :

- The performances of the equipments (for example boiler performances),
- The global efficiencies of the water/steam cycles,
- The gains or extra costs associated with the varying operating conditions of the unit (condenser pressure, exhaust temperature, excess air, fouling coefficients…),
- The best operating point with respect to the various operating conditions of the unit.

4.3 Sensitivity analysis

Then, the model allowed us to make a sensitivity analysis of the effect of air mass flow rate (excess air), ambient air temperature (combustive), temperature of the exhaust flue gases and the condenser vacuum on the thermo-hydraulic behaviour of the power plant and the efficiencies of boilers.

Figure 1 shows the evolution of the efficiencies of the boilers as a function of the ambient air temperature calculated through Dymola, the variation of the efficiencies of the boilers is +/-1% compared to the nominal value.

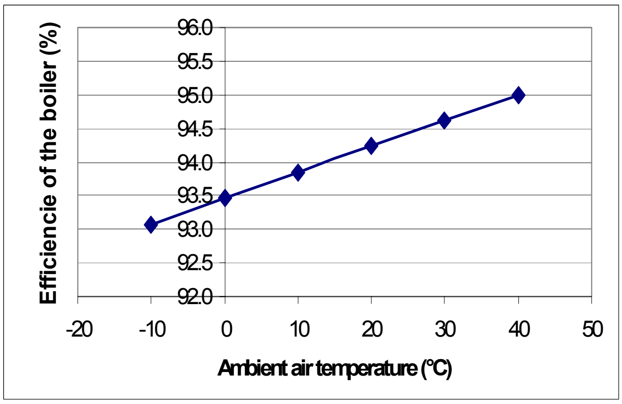

Figure 1 - Efficiencies of the boilers as a function of the ambient air temperature

Figure 2 shows the efficiencies of the boilers as a function of the excess air, the boilers efficiencies vary from 94,4% down to 92% when the excess of air passes from 10% (nominal value) to 90% (maximum value recorded on the operating data).

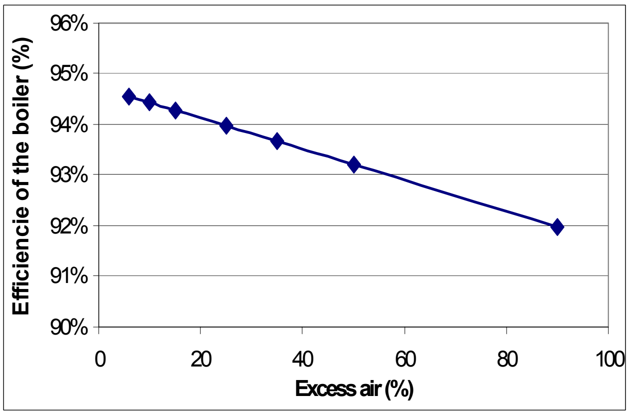

Figure 2 - Efficiencies of the boilers as a function of excess air

Figure 3 shows the efficiencies of the boilers as a function of temperature of the exhaust flue gases, the boilers efficiencies decreases by 2% when the temperature of the exhaust flue gases passes from 110 °C (nominal value) to 150 °C (maximum value recorded on the operating data).

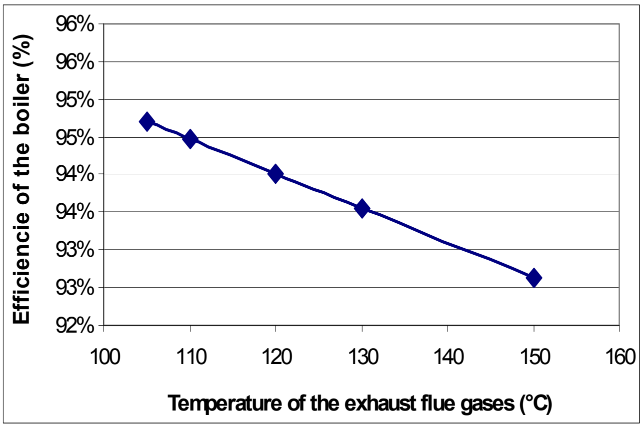

Figure 3 - Efficiencies of the boilers as a function of the temperature of the exhaust flue gases

Figure 4 shows the evolution of the power of gas turbines of the combined cycles as a function of ambient air temperature. The nominal value of power of gas turbines is 80.5 MW for ambient air temperature at 20 °C.

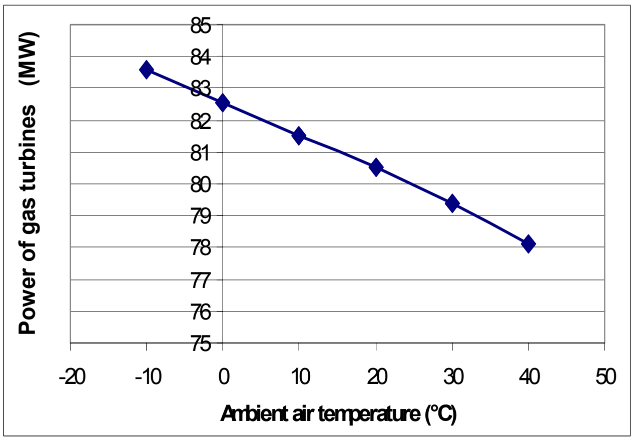

Figure 4 - Power of gas turbines of the combined cycles as a function of the ambient air temperature

Figure 5 shows the evolution of the steam turbine power of the combined cycles as a function of the condenser vacuum, the loss of the steam turbine power is about 7,5 MW, between a condenser vacuum of 50 mbar and a vacuum of 250 mbar.

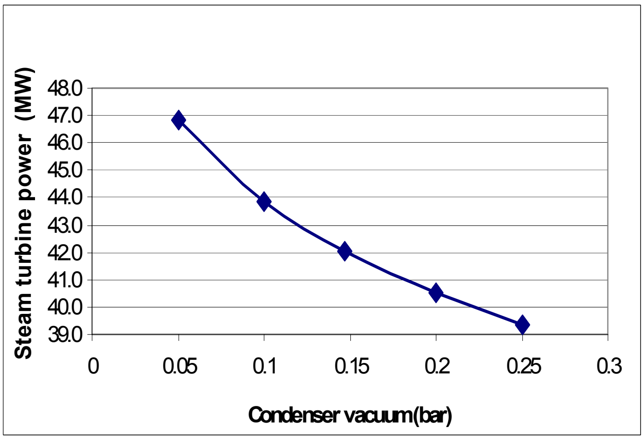

Figure 5 - Evolution of the steam turbine power of GT as a function of the condenser vacuum

4.4 Correction curves

The correction curves used to forecast the behavior of the pieces of equipment. These correction curves represent a simplified physical model of the plant, which is fed into a mathematical model used to compute on a six-week period the cheapest operating scenario which meets environmental and technical requirements.

The different correction curves create with the model are:

- **Gas boiler :** (Boiler Power / Fuel Power) ,
- **Steam turbine :** (Mechanical Power / Boiler Power) ,
- **Gas turbine :** (Mechanical Power / Fuel Power) ,
- **Combined cycle :** (Total mechanical Power / Fuel Power).

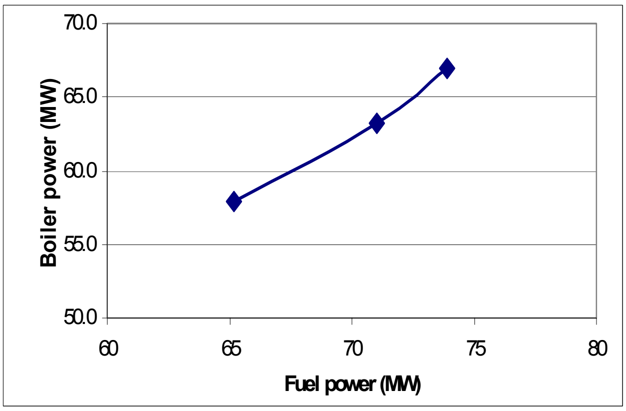

Figure 6 - Example of correction curve : Evolution of the boiler power as a function of the fuel power

5 Biomass CHP steady state model

Recent developments of environmental concerns drove states to promote renewable energies and energy efficient solutions. Some invitation to tender often are proposed so as to create new biomass CHP plants at the best operating cost.

5.1 Need

Companies answering to these invitations to tender for biomass CHP plants shall be able to choose the best configurations for the plants in order to reach the following criteria:

- The yearly average efficiency (steam + electricity) is greater than 50%;
- The plant is able to satisfy the steam demand of the customer (usually an industry) at all time;
- The yearly biomass consumption is fixed;
- The return on investment time is as low as possible.

Usual studies for this type of issue only give an efficiency at nominal point for one or two plant configuration. Models are able to provide various configurations and what-if studies in order to broaden the range of efficiency calculations and help the company to choose the best investment.

One of these companies asked us to assist them by creating and using a MODELICA Biomass CHP plant.

5.2 Building the model

This model uses the same library as the Mirafiori one. It is a fully static model. It also needs to use the same physical properties as Mirafiori.

The full model is built by connecting the component models in a technological way, so that its initial topology reflects the functional schema of the more complex plant (see Figure 7C in the appendix).

In order to be able to answer to many different situations, we created some variables in some of the component model enabling to switch itself on or off.

This multi configurations steady state model of a combined heat and power biomass plant contains 96 elementary models, generating 2162 variables and 460 non-trivial equations.

5.3 Multi – configuration calculations at normal operating condition

First the model is able to give figures at nominal point for various situations.

The same model can simulate 16 different plant configurations:

- w/wo air heater
- w/wo reheaters
- w/wo water heating
- w/wo condenser

NB: any fuel can be set into the grid furnace, but its physical equations are ideal for solid fuels (coal, waste, biomass etc.).

The plant works with a fixed biomass flow rate, it satisfies the steam demand during all the year and produces electricity with its remaining energy.

We make an inverse calculation (such as the calibration phase for Mirafiori model) with DYMOLA setting the nominal parameter to their expected value in the plant projects.

The results given by the model are :

- The efficiency at nominal point (steady state calibration),
- The electric power produced

These results at nominal point are a first step to choose the best configuration regarding the investment cost of each type of plant.

5.4 What-if steam demand varies?

Of course, the results given at nominal point are not consistent to know precisely the average performance on a one-year operation.

Consequently, we use what-if ability of DYMOLA/MODELICA model in order to realize the following computations :

- What-if simulation varying any parameter: e.g. steam flow rate,
- Economic study on a one-year typical steam demand (what-if quasi-static simulation).

The forecast of steam demand is defined as a load curve with 365 values of flow rate (one per day). It is based on measurements made by the customer on a past year considered as normal. The variation of the steam flow rate makes the global efficiency vary and changes the electric power produced.

Hence the best yearly average figures (global efficiency, electric power) are given by the model.

It gives a much better forecast of the incomes that will be generated by the plant.

5.5 Creation of a tool for non-modeller

The executable file of the model has been integrated in an easy-to-use Excel sheet for non-modelers, and it was given to our customer.

With this tool, one who is not used to models can make calculations on any plant configuration and launch what-if calculation varying steam demand.

5.6 Trigeneration issues

An absorption chiller model is being created in the static library. This could represent one-stage or two stage Water/LiBr systems on hot water or hot flue gas.

This will give us the ability to model trigeneration systems in order to compute performance figures for existing and projected plants and to simulate various behavior.

The optimal point, harder to find for a trigeneration than for a CHP, will easily be found with a DYMOLA/MODELICA model.

Conclusion

Two Steady State CHP Models were built with Modelica to evaluate the capacity of Modelica based tools to perform steady state direct and inverse computations for the sizing of power plants.

To even further reduce the effort required to do Modelica modelling and simulation for such systems, it is necessary to provide more advanced tool functionalities to handle efficiently the iterations variables, and trace the automatically generated numerical system back to its original mathematical equations, as declared by the user with the Modelica language.

Nevertheless, this work shows that the Modelica technology is mature enough to replace proprietary solutions such as LEDA for the steady state modelling and simulation of power plants.

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Appendix

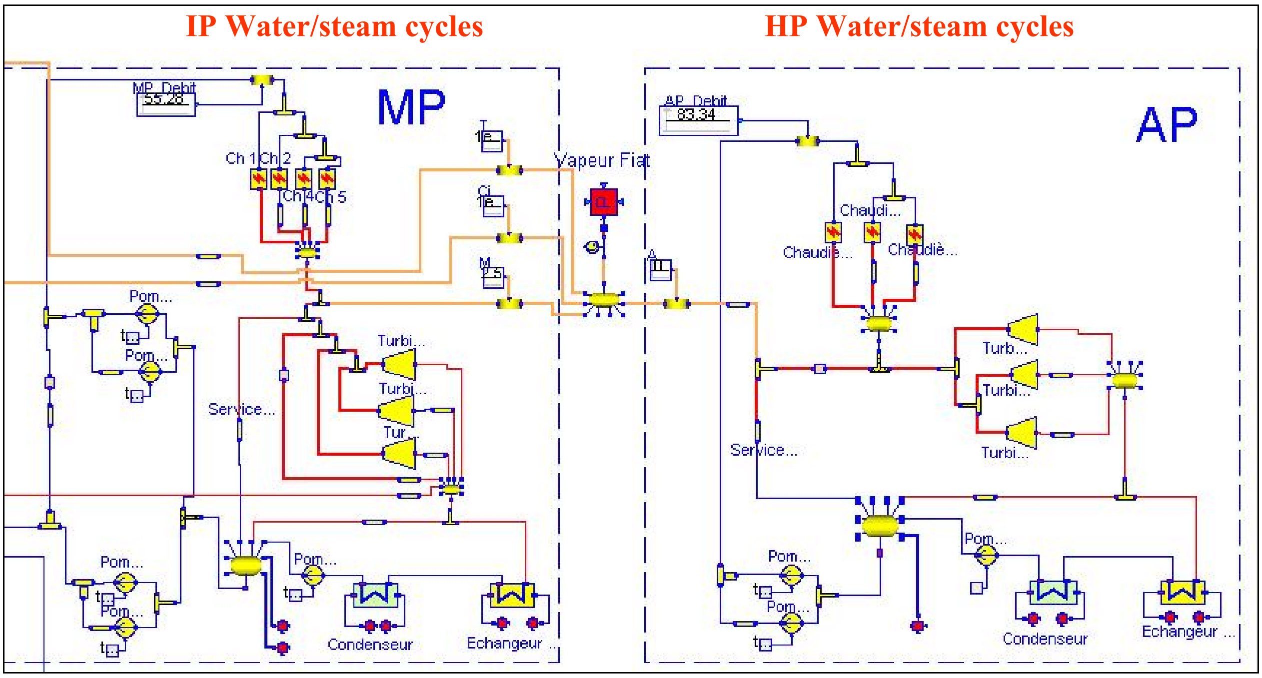

Figure 7A - Parts of the Dymola model of "Mira-Fiori

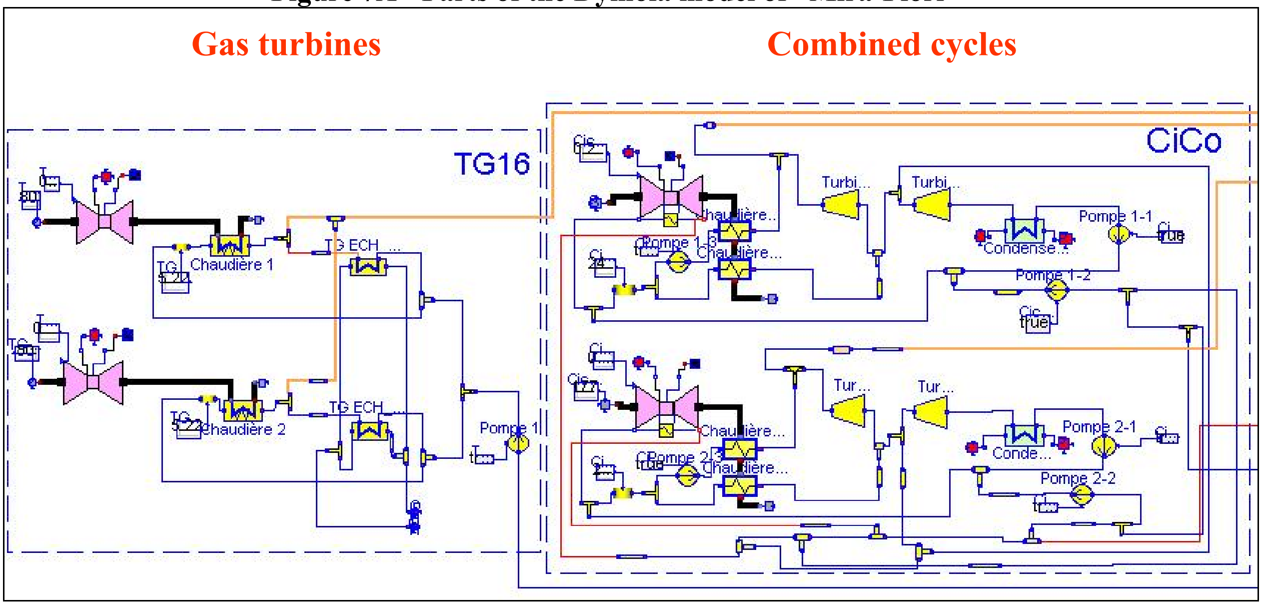

Figure 7B - Parts of the Dymola model of "Mira-Fiori

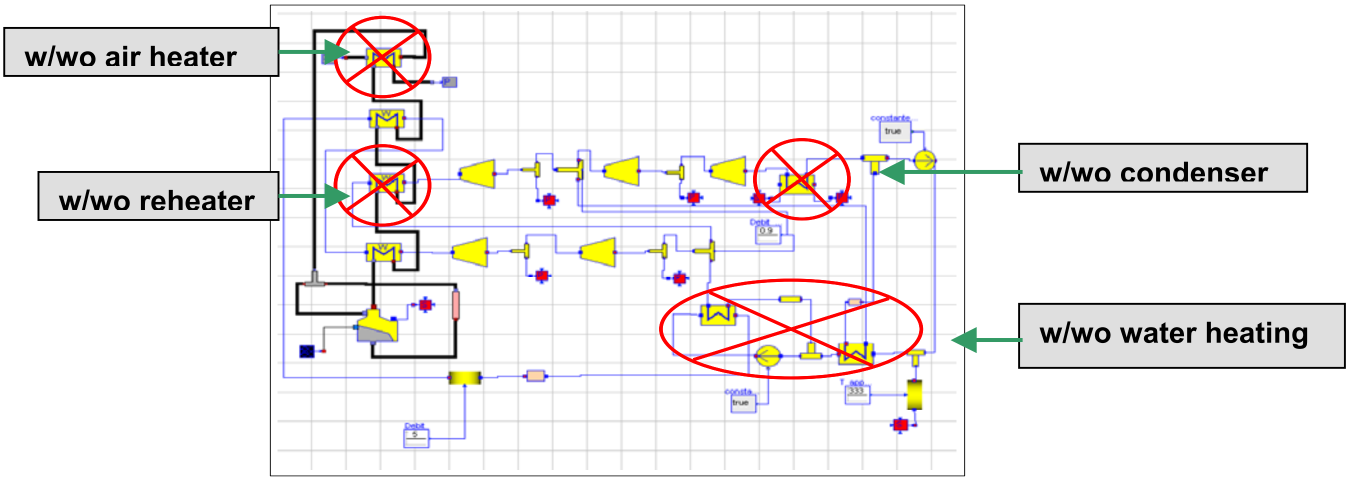

Figure 7C Dymola steady state model of a biomass CHP plant