DE-TOP User's Manual

Version 2.0 Beta

CONTENTS

1. INTRODUCTION

1.1. DE-TOP Overview

DE-TOP has been developed by the International Atomic Energy Agency as a tool for the thermodynamic analysis and optimization of nuclear cogeneration systems, such as nuclear desalination. DE-TOP models the water steam cycle (Rankine cycle) cycle of different water cooled reactors or fossil plants, and the connection between any non-electrical application.

With an intuitive graphical user interface and flexible system configuration, the user is able to select different coupling arrangements between power plant and non-electric application (single steam extraction, multiple steam extraction, backpressure operation, etc.).

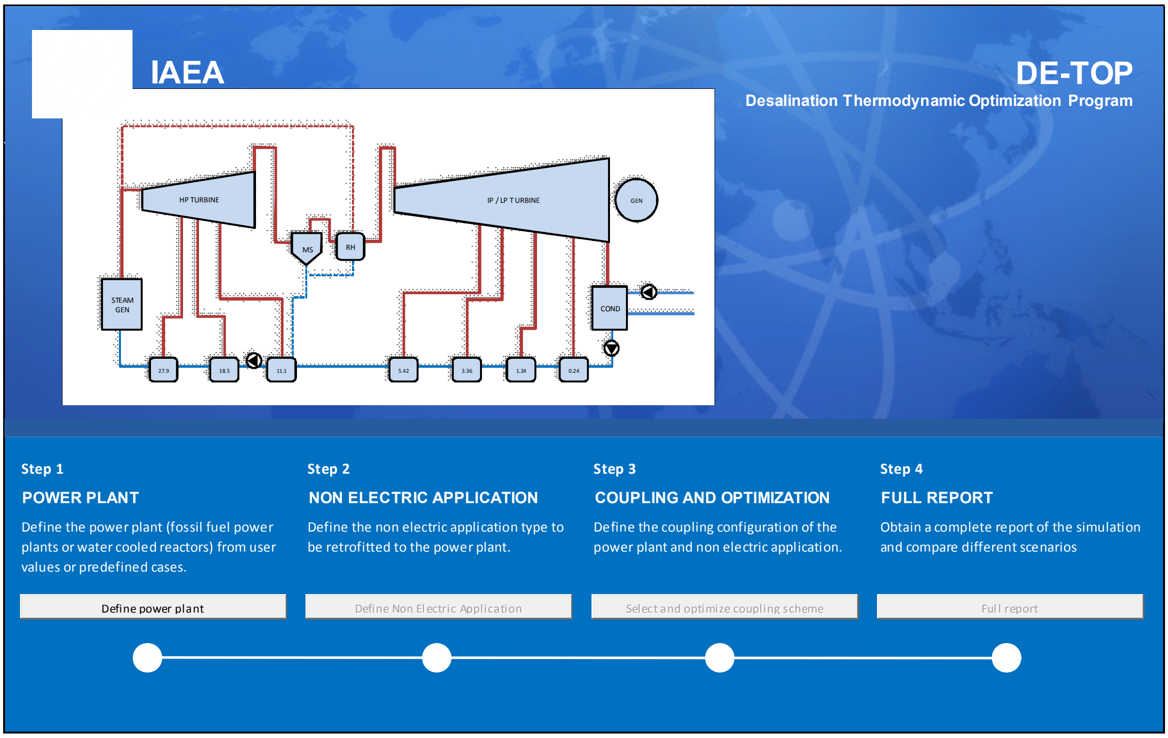

Figure 1 DE-TOP Main screen.

DE-TOP calculates energy and exergy flows of the cogeneration system and produces detailed reports for plant performance at different cogeneration modes.

The main features of DE-TOP 2.0b are:

- Detailed base-load calculation of mass and energy flows in the power plant secondary cycle
- Robust model of water/steam thermodynamic properties (T, P, enthalpy, exergy, etc.) based on the IAPWS-IF97 industrial formulation
- Fully customizable parameters for water cooled reactors and Fossil steam power plants to fit any user defined case. As well as several predefined cases (PWR, BWR, SMRs, etc.)
- Simulation operation with of non-electric applications as: Desalination, District Heating or process heat

- DE-TOP has a friendly user interface that simplify its use and allows a better understanding of the system
- Report and analysis of plant performance in single electricity production and cogeneration modes

As DE-TOP is still under continuous development, the current available version is released as a beta-version.

1.2. Background information

For an appropriated use of the program, the user is expected to have a basic knowledge of thermodynamics for energy systems, in particular steam power plants as well as cogeneration with thermal desalination systems.

The following IAEA documentation contains useful information for the use of this program:

- Introduction of Nuclear Desalination: A Guidebook
  http://www-pub.iaea.org/MTCD/Publications/PDF/TRS400_scr.pdf
- Thermodynamic and Economic Evaluation of Co-Production Plants for Electricity and Potable Water
  http://www-pub.iaea.org/MTCD/Publications/PDF/te_0942_scr.pdf
- Nuclear Heat Applications: Design Aspects and Operating Experience
  http://www-pub.iaea.org/MTCD/Publications/PDF/te_1056_prn.pdf
- Desalination Economic Evaluation Program. User's Manual
  http://www-pub.iaea.org/books/iaeabooks/6049/Desalination-Economic-Evaluation-Program-DEEP-User-s-Manual

2. DE-TOP OPERATION

2.1. Graphical interface

DE-TOP has been developed with a simple user interface which guides the user through four main steps (Figure 2). In each step the user has to input data values through forms or interactive controls in order to describe the case of study.

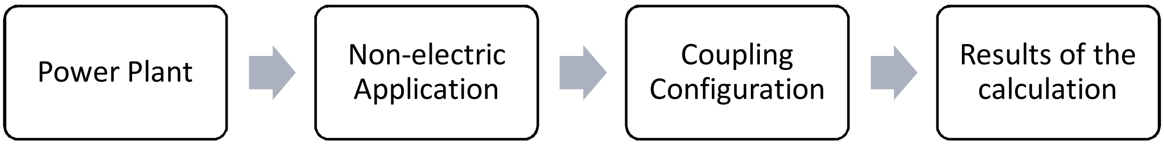

Figure 2 General DE-TOP program lay-out

The first stage is the definition of the reference power plant. This reference power plant will be first simulated by the program as a *single purpose plant* (i.e. single electricity production power plant) and then modified in further steps to analyze its performance if it operates as *cogeneration plant* (for example, Integrated water desalination and power plant). The second step is to define the non-electric application which will be coupled to the power plant, as for example thermal desalination or a district heating circuit. Once both power plant and non-electric application have been defined, in a third step the user selects the coupling configuration between them. Finally, the program runs the simulation for all the input values and returns the results of the calculations in a detailed report.

The following sections describe how to operate with DE-TOP.

2.2. Power plant model

DE-TOP models the secondary loop of a generic water cooled nuclear power plant or steam cycle conventional power plants, (Figure 3) according to fundamental thermodynamic models. Each model has been formulated with limited input to be requested from the user. Such input will be sufficient to calculate the regenerative Rankine cycle with reheat.

In order to simulate various types of power plants, other important input parameters can be modified by the user including: thermal capacity, live steam conditions, reheat pressure ratio, feedwater preheating conditions and efficiencies. Site-specific data such as cooling water temperature is also modelled as an input necessary to show the impact of ambient temperature to the performance of the dual-purpose plant. DE-TOP uses the input data to simulate the thermodynamic model of the power plant, solving all mass and energy flows using thermophysical properties which will be calculated based on a built-in databank, such as temperature, pressure, specific enthalpy and entropy.

2.2.1. Model description

A brief description of the theoretical thermodynamic process considered in DE-TOP involves the heat generated (from nuclear reactor or conventional boiler) and transferred to the secondary side, via a steam generator. The generated steam is expanded in the high pressure (HP) turbine where partial flows are extracted and delivered to feed high pressure heaters and deaerator. The remaining steam is directed to the moisture separator and reheater where moisture content is removed and the remaining dry steam is superheated by a portion of live steam to decrease steam moisture in the last low pressure (LP) turbine stages. In the LP turbine, steam is expanded to the condenser pressure. The working steam passes through the condenser where condensation takes place, and condensate is pumped through the LP regenerative heaters to the deaerator, from which the water is delivered by the main feedwater pumps back into the steam generator through the HP heaters.

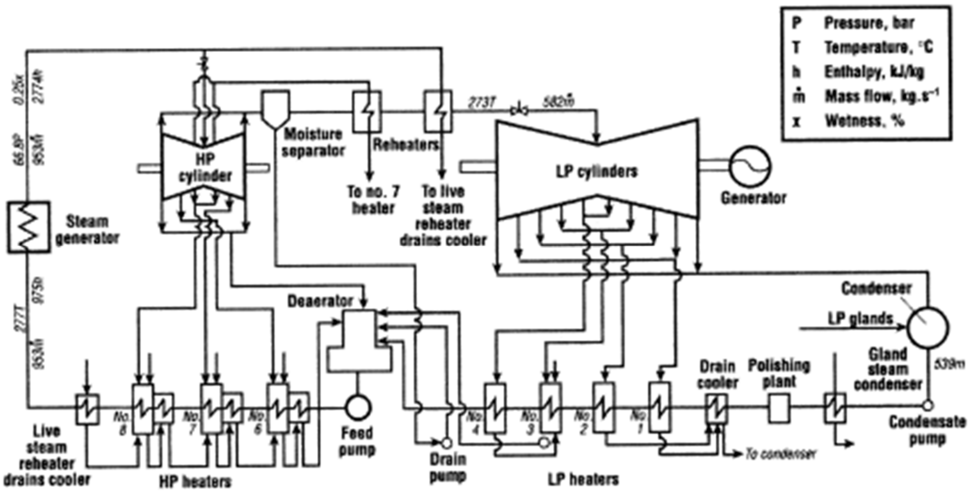

Figure 3 Schematic diagram of a large nuclear power unit secondary cycle

2.2.2. Data input

The user introduces all required information through forms. DE-TOP is developed to minimize the amount of required input by the user, simplifying its use for non expert users. Required data input is shown in the "Main Parameters" tab (Figure 4). This tab includes the following fields:

- **Case**: default case studies available in the program. The user can select any case and modify later the parameters.
- **Thermal input**: heat thermal input to the steam generator.
- **Live steam pressure**: live steam pressure. Steam pressure leaving the steam generator.
- **Live steam temperature**: live steam temperature. In nuclear power stations steam is usually at saturated conditions. for fossil plants is superheated steam
- **Reheat type**: nuclear power stations reheat the steam exhausted from the high pressure turbine with a portion of live steam. While Fossil power plants redirect the steam exhausted to the steam generator.
- **Reheat pressure**: reheat pressure in the reheater or Moisture separator and reheater (MSR)
- **Reheat temperature**: reheat temperature of steam after the high pressure turbine. For nuclear power stations this temperature has to be below the live steam temperature.
- **Final feedwater temperature**: temperature of the condensate before the steam generator.
- **Number of feedwater preheaters**: number of preheating stages including deaerator

- **Deaerator position in the feedwater line**: position of the deaerator in the feedwater line starting after the condenser. (For example, Position = 3 means condenser, two preheaters and then the deaerator.)
- **Condensing steam pressure:** pressure of condensing steam within the condenser.

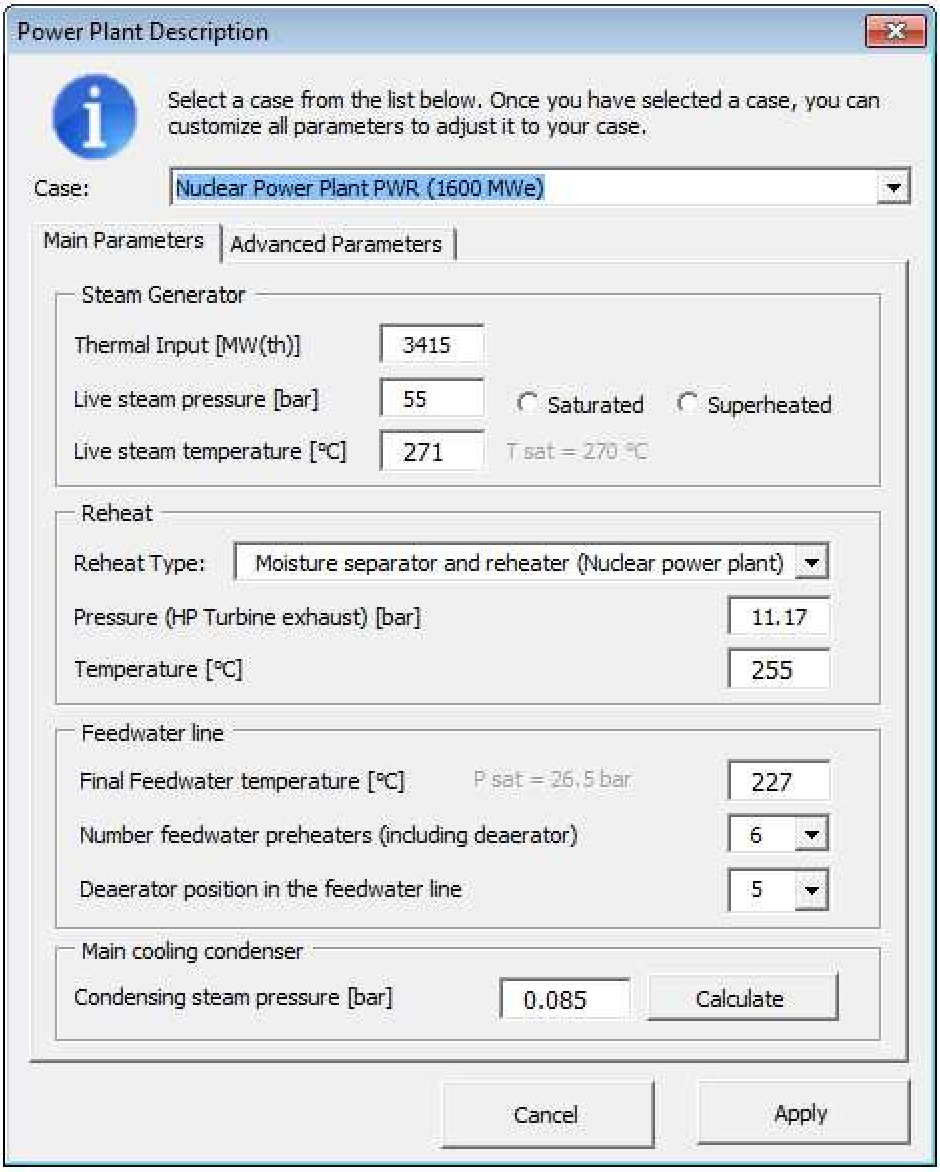

Figure 4 Power plant data Input form. Main Parameters tab.

The condensing pressure is a function of the ambient temperature as well as the specifications of the cooling system. This pressure can be introduced directly by the user in the form, or calculated. By clicking "calculate" another form pops-up for the cooling system specifications (Figure 5).

- **Type of cooling system**: Once through cooling is the only option enabled in this version.
- **Cooling water temperature**: temperature of the cooling medium, seawater or river.

- **Cooling water temperature rise in condenser**: temperature increase of the cooling water circuit before and after the condenser
- **Condensing approach temperature**: condenser Specification. Values can be in the range of 5 to 10°C.

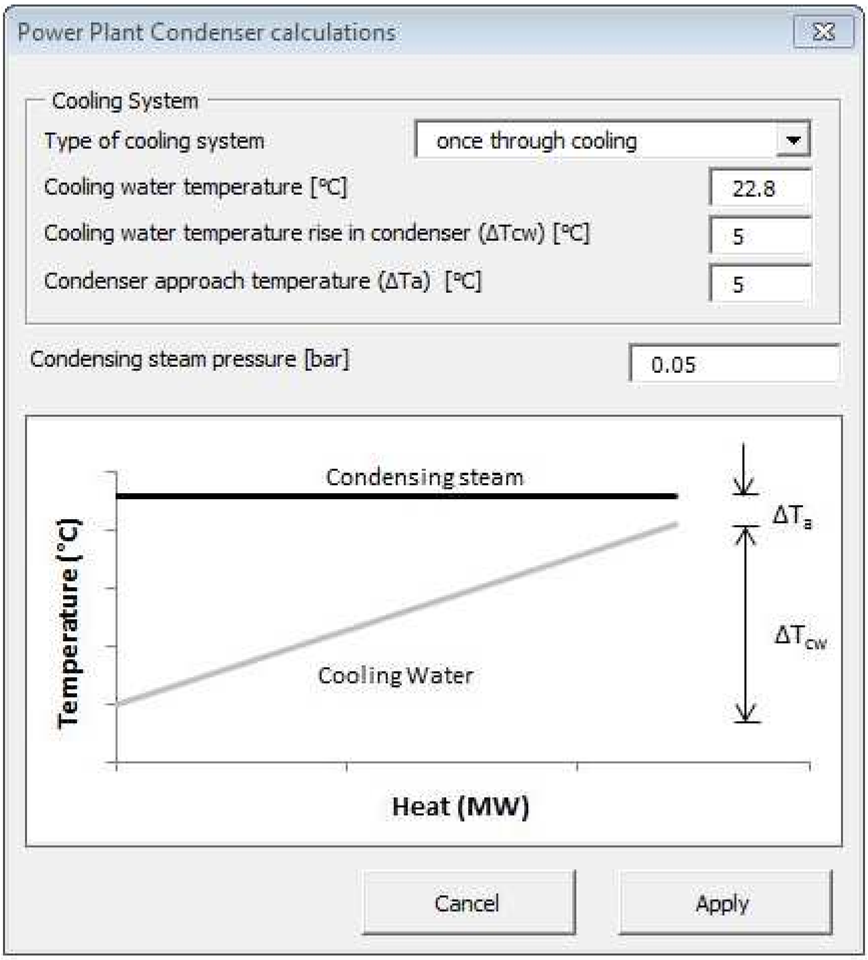

Figure 5 Data input form in DE-TOP for Condenser pressure calculation

The Advanced Parameters tab (Figure 6), include other parameters which influence the simulation but are established by DE-TOP as default values to simplify the plant simulation. The user can modify these values according to his personal case.

The Advanced parameters are:

- **Steam generator efficiency**: Applicable for fossil fuelled power plant. In Nuclear power stations is considered as 1.
- **Turbine and pump efficiencies**: High Pressure (HP) Intermediate Pressure (IP) and Low Pressure turbine and pump isentropic efficiencies.
- **Power plant Auxiliary loads**: power plant auxiliary loads consumption, as a percentage of the gross power output. This parameter includes Power consumption of auxiliary systems in the primary loop, secondary loop and cooling systems in case of nuclear power stations.

- **Generator efficiency**: Efficiency of energy conversion from mechanical to electrical output in the electrical power generator.
- **Feedwater preheater pressures**: Pressure of the steam extraction to drive the feedwater preheaters.

  In order to simplify the power plant simulation, DE-TOP estimates the position of the feedwater preheaters (i.e. the operating pressures of each feedwater preheater). However, the user is able to customize these values here, in order to fit them with the case of study. For the fields of preheater pressures where there are no preheaters simulated leave the value zero. DE-TOP simulates the feedwater preheaters as direct contact heaters.
- **Complete model:** Link to the complete calculations sheet, where additional parameters can be modified. This feature is recommended only for advanced users.

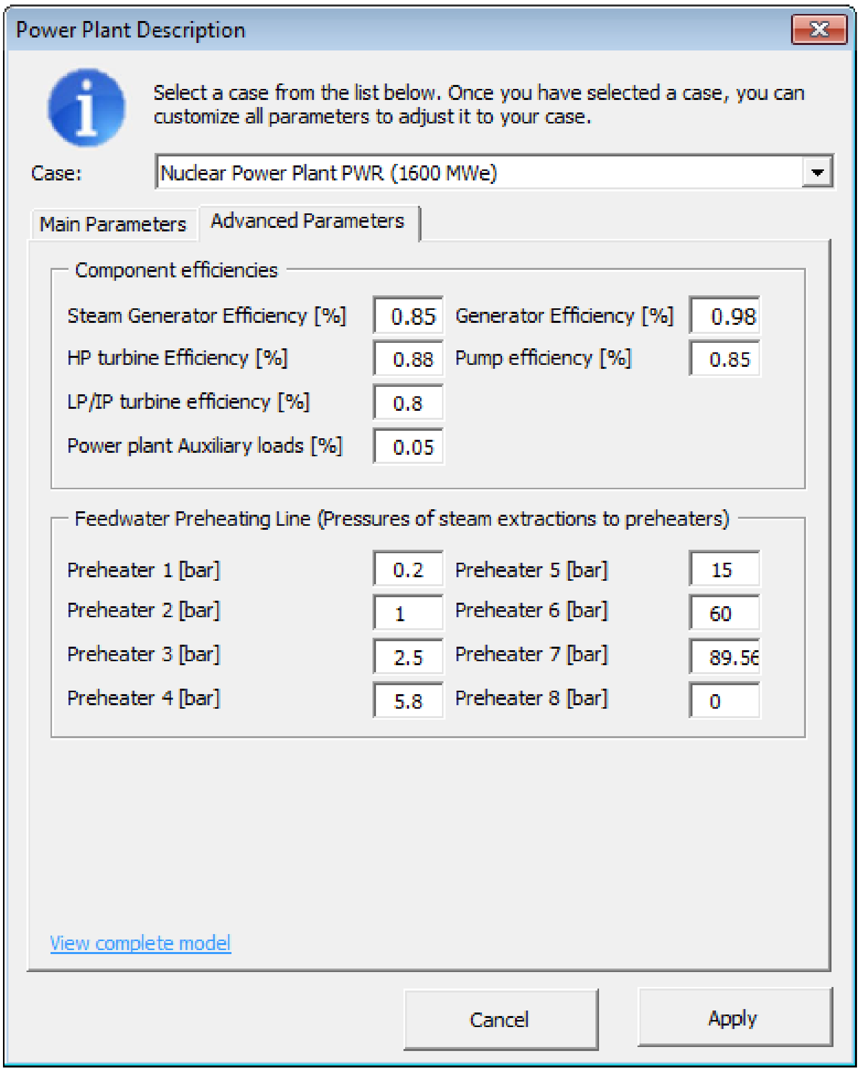

Figure 6 Power plant data Input form. Advanced Parameters tab.

Once all parameters have been introduced click “Apply” and DE-TOP will simulate the reference power plant and take the user to the results of the simulations page (Figure 7).

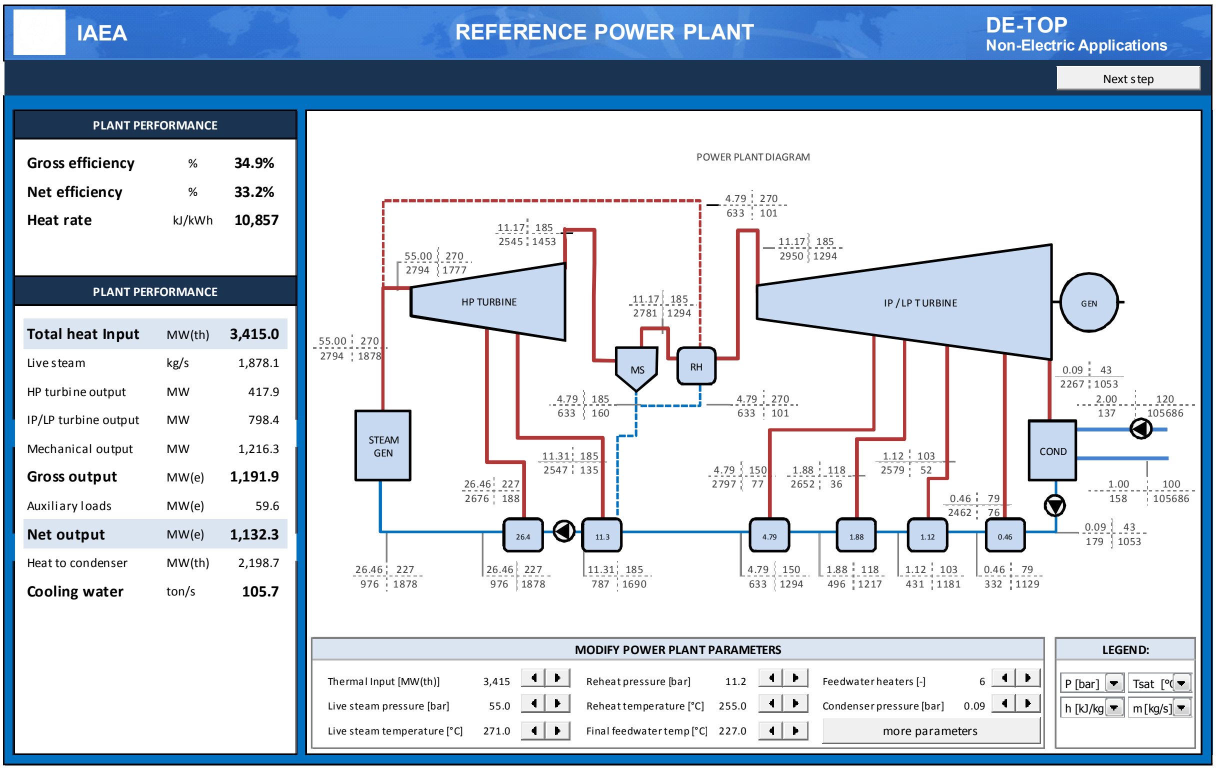

Figure 7 Results of the simulation for the reference power plant.

The main results of the simulation are shown in the reference power plant page. The screen is divided into the following areas:

- **Plant performance**: this area shows the main outputs calculated for power plant water steam cycle.
- **Flow diagram**: simplified power plant diagram where components, steam and feedwater flows are depicted. Thermodynamic properties for each flow are shown in labels.
- **Power plant parameters**: interactive controls area where the user can change the previously defined parameters. This feature allows the user an immediate observation of the effects of each parameter on the power plant performance.
- **Legend**: here the properties shown on the pipe labels can be changed. The available properties are pressure (P), temperature (T), entropy (s), steam quality (q), enthalpy (h), saturation temperature of the fluid (Tsat), exergy (x), mass flow (m).

By clicking the button “Next step” the user is returned to the main screen to proceed with following steps.

2.3. Non-electric application model

Non-electric applications use energy, usually heat in the form of steam, from the power plant and deliver it to the heat consumers or use it to obtain another product, as for example fresh water from desalination processes. DE-TOP (2.0b Beta) includes models for the following Non-electric applications:

2.3.1. Thermal desalination processes

In thermal desalination processes raw water is boiled and the vapour condensed as pure water (distillate). Thermal desalination technologies included in this version are multi-stage flash (MSF) and multi-effect distillation (MED) and thermal vapour compression (TVC)

2.3.1.1.Model description

DE-TOP model for the desalination is based on the estimation of the gain output ratio of the plant (GOR). The GOR is the ratio of the mass of desalted water produced per mass of steam consumed.

DE-TOP estimates the GOR using the same desalination model as the IAEA's Desalination Economic Evaluation Software (DEEP). GOR estimation methods are described on 0. Once the gain output ratio has been estimated then the required heat contained in the steam extraction for the design size of the desalination plant can be calculated as follows:

$$Q_{ext} = \frac{D}{GOR \cdot h_{lv_{ext}}}$$

Where $h_{lv_{ext}}$ is the latent heat of motive steam in the brine heater of the MSF plant or the first effect for MED plants. The selection of the steam extraction in order to meet this required heat amount will be performed by the user in the following DE-TOP step.

2.3.1.2.Data input

To simulate the desalination system, DE-TOP requires the following design parameters:

- **Desalination technology:** Multi-stage flash (MSF) and multi-effect distillation (MED) and thermal vapour compression (TVC)
- **Seawater TDS:** Feed water salinity, defined according to the total dissolved solids (TDS). This is measured in milligrams per litre (mg/l) or parts per million (ppm). The two units are generally interchangeable in dilute solutions.
- **Top brine temperature:** Maximum temperature at which the brine is heated up in the brine heater of a MSF plant or the first effect of a MED plant. This value is limited to avoid scale formation which affects the efficiency of the desalination processes

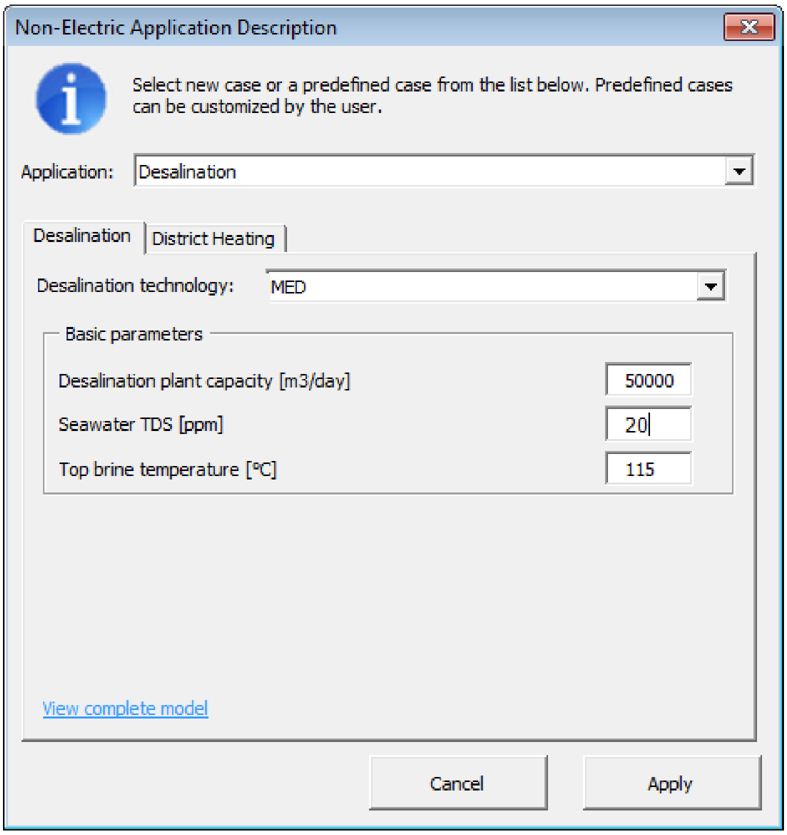

Figure 8 Non-electric application data input form. Desalination parameters

2.3.2. *District heating*

District heating is a system for distributing heat to residential, commercial or industrial users. Extracted steam from high and/or low pressure turbines is fed to heat exchangers to produce hot water/steam, which is delivered to consumers.

2.3.2.1.Model description

DE-TOP district heating application simplified model, simulates the delivery of heat in form of hot water to a single user the distribution point for residential users. Thus, given the required amount of heat to be provided, and the specifications of the transport line, DE-TOP estimates the main performance parameters of the system (pumping power, heat loses in pipes, etc.). The district heating model is described in the advanced user calculation sheet.

2.3.2.2.Data input

To simulate the district heating system, DE-TOP requires the following design parameters:

- **Heat to district heating circuit:** required heat to be distributed to the consumers
- **Temperature to target:** Temperature of the hot water delivered to consumers
- **Return temperature:** Temperature of the returning cold water
- **Main line operating pressure:** Operating pressure at the District heating circuit
- **District heating main line length:** Length of the main water transport line of the District heating circuit

- **Number of main lines to target:** In large scale district heating circuits can be more than one
- **Main pipeline internal diameter:** Diameter of the main distribution line

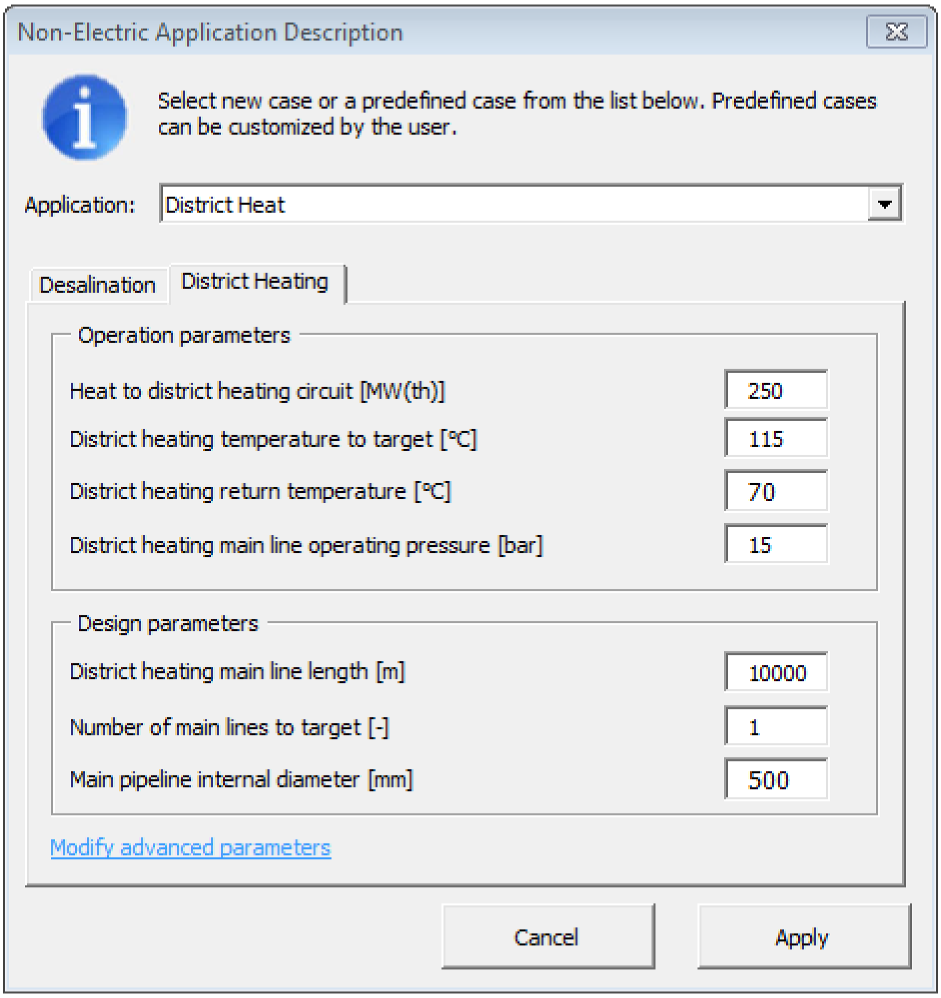

Figure 9 Non-electric application data input form. District heating parameters

2.4. Coupling configuration selection

Once the non-electric application model has all required parameters for its simulation, the following step is to define the heat source for the application. DE-TOP simulates a cogeneration plant, where all required energy is supplied by the power plant. In the following screen (Figure 10), DE-TOP interface allows easy selection of the points for steam extraction and condensate return.

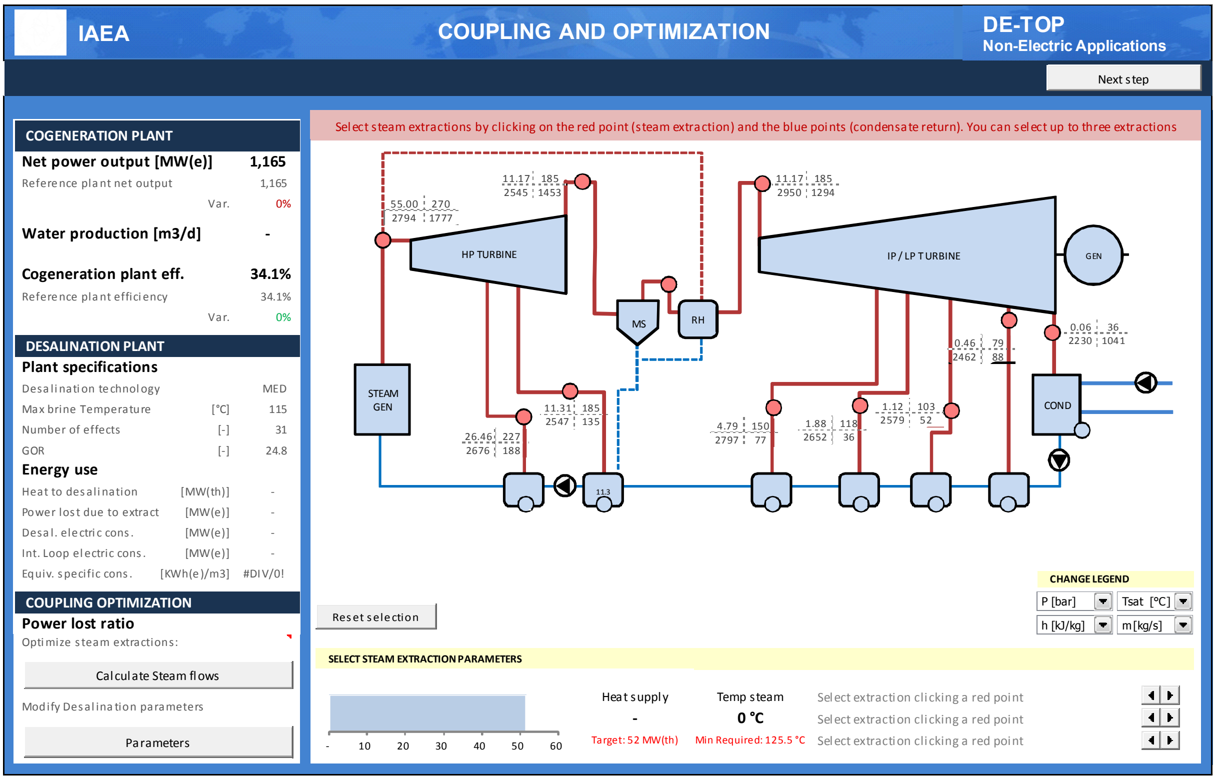

Figure 10 DE-TOP Coupling configuration screen. Red points in the flow sheet diagram are possible steam extraction points. Blue points represent possible location of condensate returns

2.4.1. Possible steam extraction points

Steam has to be extracted from the power plant cycle in the same way that is extracted for the feedwater heaters, but with additional safety measures to prevent any potential carryover of the radioactivity from the water/steam cycle to the desalination process. In such a case, an isolation loop is placed between extracted steam and desalination plant, acting as a third physical barrier against possible radioactive contamination. Once the steam from the power plant has released its latent heat by condensation on the non-electric application side, it is returned to the power plant and injected in an appropriate location.

Possible steam extraction points are limited by two main constraints: the energy needs for the non-electric application, which defines the amount of steam to be extracted and the application features or technology (desalination technologies as MSF, MED and LT-MED operate at different temperature ranges), which defines the quality of the heat needed. Thus, steam has to be withdrawn from a point in the power plant where its saturation temperature is above the non-electric application requirements (i.e. max brine temperature for desalination), considering an additional temperature drop due to the intermediate loop and minimum temperature approach in heat exchangers. Technical constraints from the power plant side, such as maximal extraction flows in turbine bleed points, or specific layout in the plant may limit the feasible extraction locations but are not considered in DE-TOP to allow flexible simulation.

2.4.2. Selection of single steam extraction

The dashboard located under the flow sheet diagram (Figure 11) shows the minimum requirements for the selected application. As an example for a desalination plant simulated for production of 50000 m^3/day (Figure 8), a minimum of 57 MW(th) of energy flow in form of steam with a saturation temperature of 125.5ºC or more have to be provided to the non electrical application.

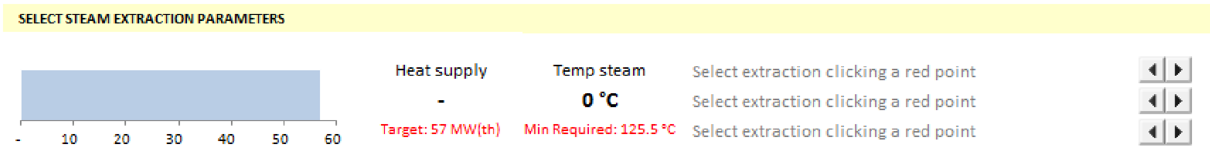

Figure 11 Coupling configuration dashboard before steam extraction selection.

To select an extraction click on any of the red points in the flow sheet diagram and select the desired mass flow extraction on the Coupling configuration dashboard (Figure 11). In our example, one of the steam extractions for preheating purpose as point for steam extraction for the non-electric application (Saturation temperature of 150°C).

After delivered to the non-electric application, the steam flow transfers its latent heat and is returned to the power plant as condensate. The user selects the return location for the previous extraction by clicking on a blue point, on the flow sheet diagram (Figure 12).

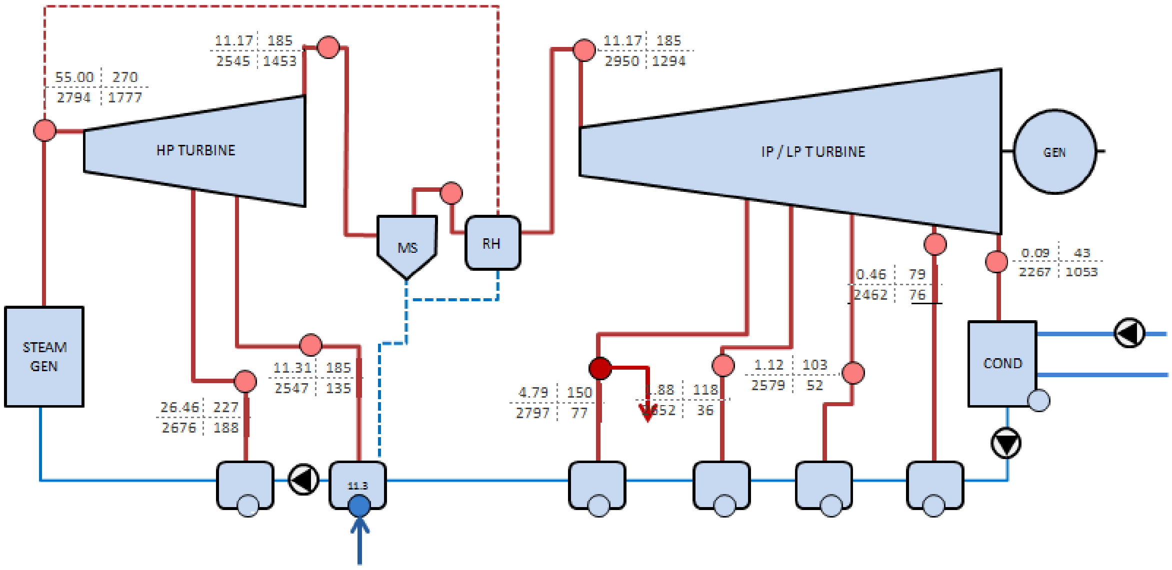

Figure 12 Flow sheet diagram after selection of the extraction and condensate return.

Now the user introduces the amount of steam to be extracted. Although the size of the non-electric application has been already defined, and therefore, the required amount steam can be calculated automatically, DE-TOP allows the user to freely select the steam mass flow (kg/s) for training purposes.

User defined extraction mass flow

The amount of steam to be extracted is defined in the red box which appears on the dashboard (Figure 13). In the working example the selected mass flow has been 20 kg/s. Immediately, the software provides the equivalent flow in terms of energy and shows graphically on a horizontal chart the amount of required heat to meet the previously defined plant size or production (blue bar) and the actual amount of energy provided (red bar).

DE-TOP simulates dynamically all performance parameters, which are shown in the left column, to show the user the effect of such extraction.

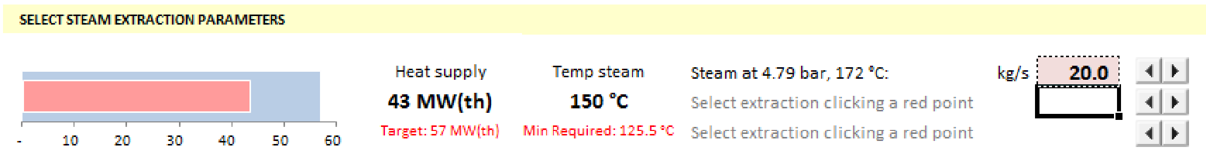

Figure 13 Coupling configuration dashboard.

DE-TOP calculated extraction mass flow

The required amount of steam to be provided to the non-electric application can be automatically set by DE-TOP by clicking the button “Calculate Steam flows” on the left column of the users interface (Figure 14).

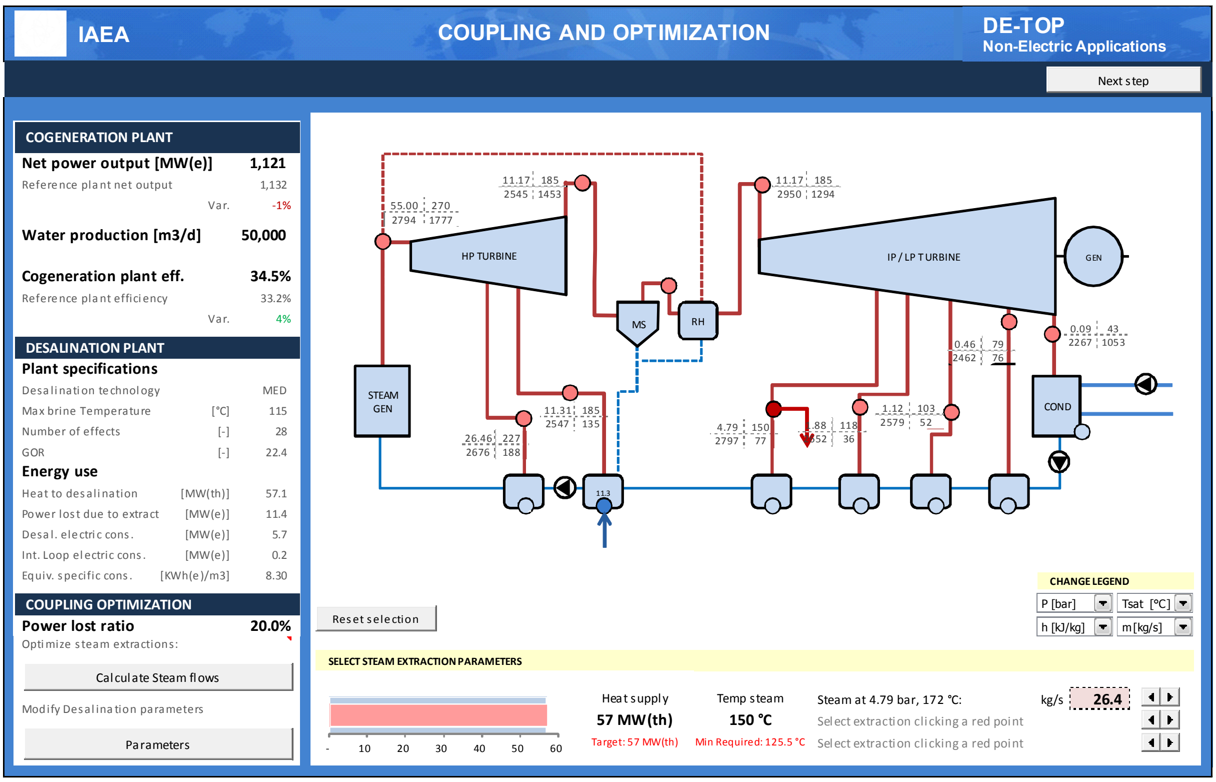

Figure 14 Selected coupling flow sheet. Cogeneration plant parameters are shown on the left column. The Power lost ratio acts as an indicator and gives an idea of how optimized is the user selected lay-out.

Removing extractions

By clicking again on a previously selected red point, both the extraction and the condensate return will be removed.

2.4.3. Selection of multiple steam extractions

In some cases, multiple steam extractions are selected to minimize the power lost on the power plant side, or to allow flexible operation of the system. District heating applications usually include two or three extractions to heat up gradually the district heating circuit, thus reducing irreversibilities on the heat transfer. DE-TOP allows up to three extraction points (Figure 15).

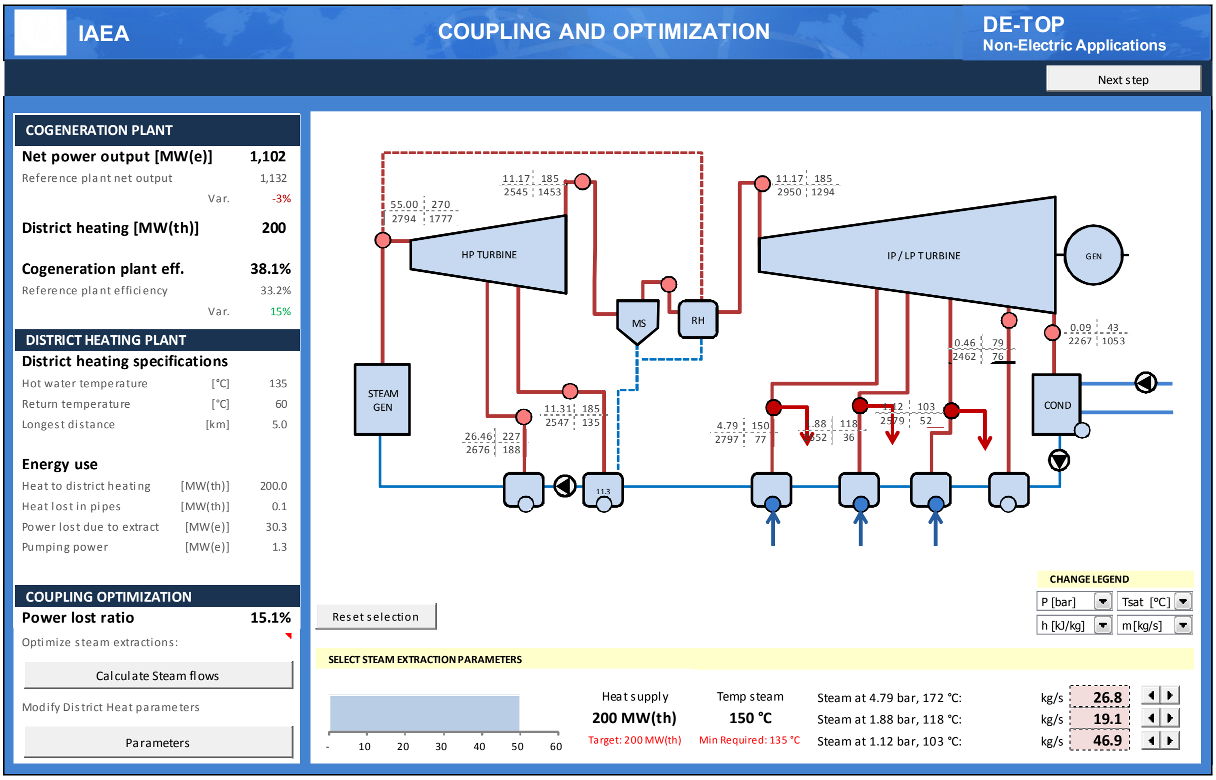

Figure 15 Coupling configuration for district heating application, example for multiple extraction points.

To select multiple extractions, after having selected the first pair of points (extraction point and condensate return), simply click on another red point for a new steam extraction and a blue point to define its return location. Condensate return locations can concur on one same point (for example the deaerator feedwater tank).

DE-TOP has been developed for training and educational purposes, therefore there are no restrictions in the selection of the coupling configuration. The user is free to select any extraction, but not every extraction will be feasible. In our previous example, where a minimum temperature of steam of 125.5ºC is required, the user can select an extraction from the low pressure turbine exhaust (wet steam at 43ºC). Since this case is not feasible, the simulation will show errors.

2.5. Final report

The final report shows all performance parameters for both, single electricity production power plant, and cogeneration dual purpose power plant. Figure 16 and Figure 17 show the final report for a standard pressurized water cooled reactor power plant operating together with a MED thermal desalination plant and a district heating system respectively.

The final report includes detailed information about the power plant side and the non-electric application. The following indices can assist in the decision making of the coupling configuration for any given plant taking into consideration other characteristics, such as reactor and desalination plant capacity, desired flexibility in operation and other site specific constraints:

Thermal utilization

Due to synergies involved, cogeneration systems have increased overall efficiency. An index that is frequently used to characterize the performance of a cogeneration system is the thermal utilization factor (TU) that shows the percentage of primary energy utilized by the end user by means of:

$$TU = (W + Q_u)/F$$

Where W is the work produced by the power plant; Q_u is the useful heat delivered to the desalination plant and F is the energy in the fuel supplied to the dual-purpose plant.

Total power requirements

The increased efficiency comes with a cost. The steam extracted for the non-electric application causes a drop in power generation which is strongly dependant on its extracted conditions and auxiliary equipment of the non-electric application. The total power requirements include electric power generation reduction due to reduced steam flow through the turbines and electric consumption of auxiliary loads (pumping and other equipment) of the non-electric application.

The reduction on turbine internal efficiency due to the reduced steam mass flow is not significant for small amount of steam extractions and therefore is not modelled in DE-TOP. However this effect is analogous to the turbine efficiency in part load operation; high relative amounts of steam extracted cause a decrease in the turbine's efficiency due to its bigger divergence from the nominal operation and therefore a further decrease in the power output.

Power lost ratio

The power lost is the difference between the power output of the reference plant (W_T^{ref}) and the power output of the cogeneration plant (W_T^{cogen}) by means of: $\Delta W = \left(W_T^{ref} - W_T^{cogen}\right)$

For the comparison of different systems it is useful to calculate the power lost ratio, which is defined as the power lost in the power plant to the amount of heat delivered for the non-electric application process, e.g. for water thermal desalination a power lost ratio of 10% implies that for each 100 MW(th) extracted the net nominal power output is decreased by 10 MW(e).

$$Power\ lost\ ratio = \frac{Power\ lost}{Useful\ heat}$$

As a first approximation, the reduced output of the steam turbines ΔW (mechanical equivalent of the steam) is estimated as the work that would have been produced in the steam turbine if the extracted mass flow was expanded from the extraction point to condenser conditions.

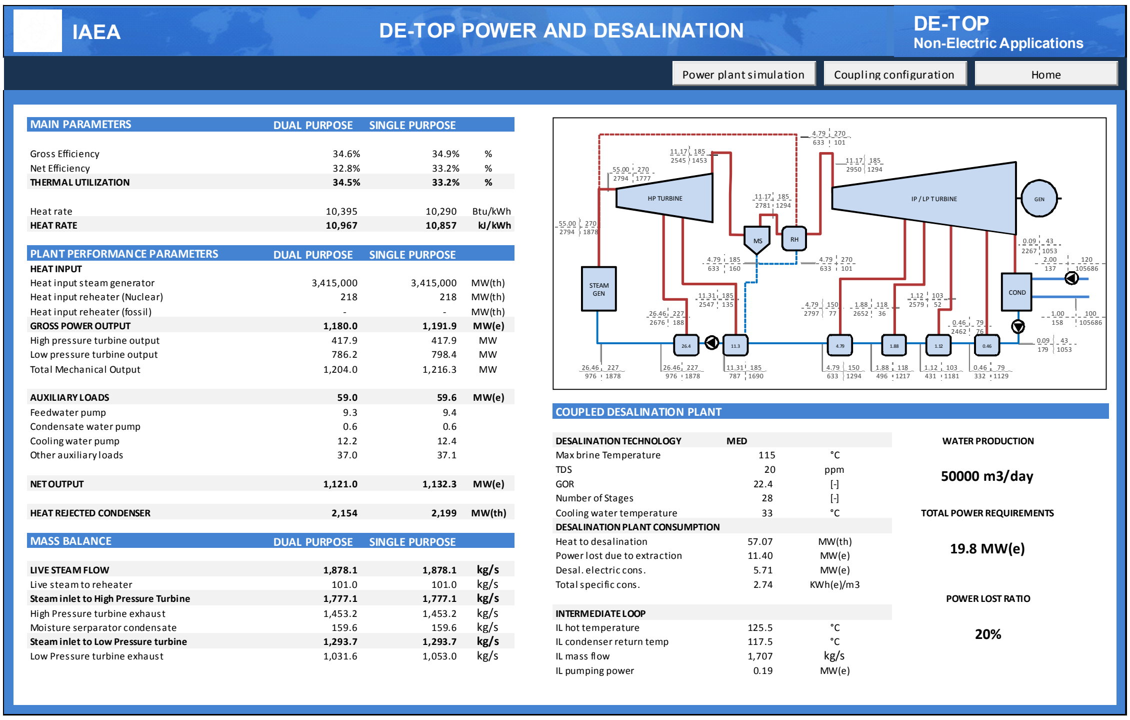

Figure 16 DE-TOP Final report for the combined power and MED thermal desalination plant.

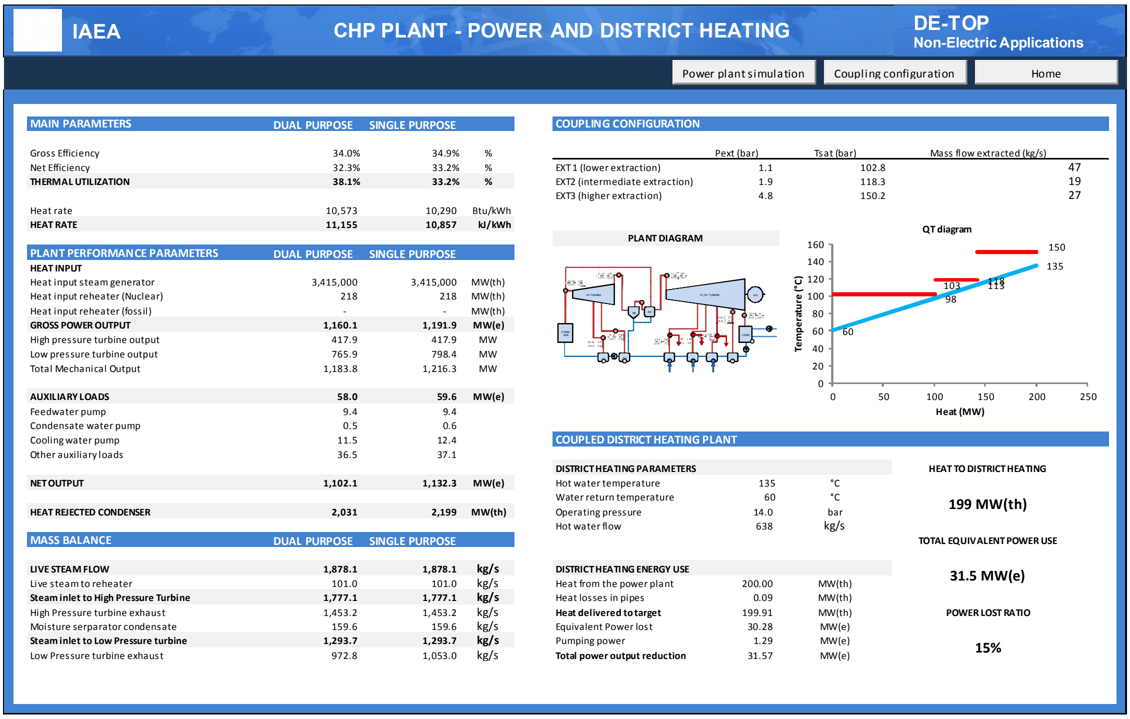

Figure 17 DE-TOP Final report for the combined heat and power plant with district heating application.

3. TECHNICAL DESCRIPTION

3.1. DE-TOP Structure

DE-TOP has been developed in multiple layers with Microsoft Excel and Visual Basic, characterized by its user friendliness and simplicity. Software's structure is presented in (Figure 18). The structure consists of three main modules: the graphical user interface (GUI) for input and output, the processing modules which perform the calculations for both the power plant and the cogeneration system, and the data module which supports the processing module with a complete steam properties library.

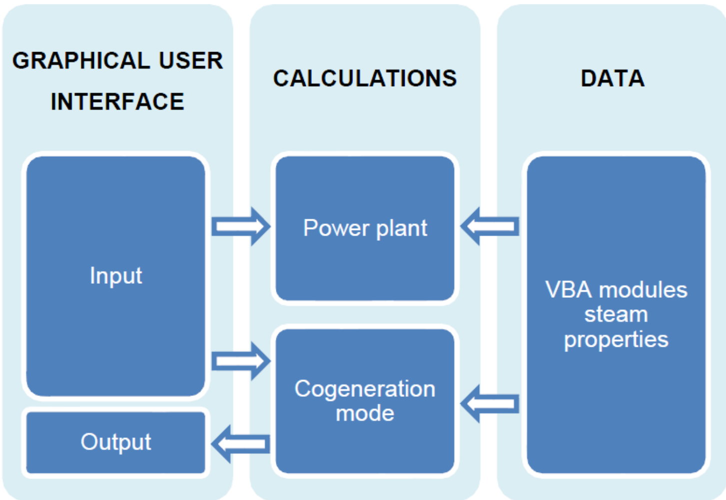

Figure 18 DE-TOP Structure

DE-TOP runs a Visual Basic module for the calculation of thermodynamic properties for steam and water in accordance with the IAPWS industrial formulation of 1997. Enthalpy and entropy as a function of temperature, pressure and steam quality along with their backwards functions have been modelled in detail in order to assure the accuracy of the system.

3.2. DE-TOP Calculation method

The current power plant model used in DE-TOP is rather a simplified model of conventional light water reactors, briefly described in section 2.2. The following assumptions were made: the preheating line employs direct contact heaters which heat the feed water to the saturation temperature of the bled steam in each heater, pressure losses in preheaters as well as along connecting pipes from the turbine to these units are neglected and the increase of enthalpy passing through the heater pumps is negligible.

After all required parameters are introduced, DE-TOP creates the system matrix which includes for each apparatus the energy balance and the mass balance. For closed cycles like the water steam cycle on the power one equation is removed to obtain a squared matrix where the number of equations is equal to the number of pipes.

With the system matrix created, DE-TOP calculates for each pipe, all thermodynamic properties (Pressures, temperatures, enthalpies etc.) according to the thermodynamic processes in each component.

Finally enthalpies and rest of coefficients are substituted in the relevant energy equations. The system is solved using algebraic methods and mass flows and performance parameters for the system are obtained.

3.3. Desalination plant Module

DE-TOP uses the same desalination model as the IAEA's Desalination Economic Evaluation Software (DEEP). The GOR can be estimated for MSF plants as follows:

$$GOR = \frac{\lambda_h}{c_h \cdot (\Delta T_{bh} + \Delta T_{bpe})} \cdot (1 - e^{-c_{vm} \cdot \Delta T_{ao} / \lambda_m})$$

Where

λ_h = latent heat of heating vapour, kJ/kg

λ_m = average latent heat of water vapour in MSF stages, kJ/kg

c_h = specific heat capacity of feedwater in brine heater, kJ/kg/K

c_{vm} = average specific heat capacity of brine in MSF plant, kJ/kg/K

ΔT_{bh} = brine heater feed temperature gain for MSF, °C

ΔT_{bpe} = boiling point elevation, °C

ΔT_{ao} = overall working temperature range, °C

ΔT_{ae} = average temperature drop per effect, °C

ΔT_{ph} = Preheating feed temperature gain, °C

The GOR is estimated for MED plants as the number of effects times the efficiency of the plant. DE-TOP uses a default value for MED efficiency of 0,8. This value can be modified on the advanced user model calculations sheet.

The number of effects can be estimated given the cooling water temperature, the top brine temperature and the average temperature drop between stages.

$$\Delta T_{ao} = \left(T_{mb} - (T_{cw} + \Delta T_{reject}\right)$$

$$N_{emed} = \Delta T_{ao} / \Delta T_{ae}$$

Where $\Delta T_{ao}$is the Overall water plant working temperature, N_{emed} the number of stages, T_{mb} the top brine temperature, T_{cw} the cooling water temperature, ΔT_{reject} the reject or cooling stage range in the distillation plant and ΔT_{ae} the average temperature drop between stages.

For the case of thermal vapour compression units coupled to MED or MSF systems, the GOR model is generalized as follows:

$$GOR_{tvc} = GOR \cdot (1 + R_{tvc})$$

Where R_{tvc} is defined as the ratio of entrained vapour flow to motive steam flow, an input design parameter. DE-TOP uses a default value for R_{tvc} = 1