Greenius Manual

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Introduction

greenius is a powerful simulation environment for the calculation and analysis of renewable power projects such as

- Solar thermal parabolic trough power plants,
- Solar thermal power towers,
- Photovoltaic systems,
- Wind parks,
- Dish/Stirling systems or
- Fuel Cells.

This program offers a unique combination of detailed technical and economical calculations as they are needed for planning and installation of renewable power projects. **greenius** is a simulation environment with comfortable user interface for the analysis of solar thermal power plants, photovoltaic systems and wind parks.

greenius distinguishes itself by numerous export possibilities for intermediate and final results. Almost all contents of tables and graphics can be copied to other Windows applications or can be saved in other formats. The calculation results are detailed and the extended simulations perform very fast.

Since 2013 **greenius** is distributed free of charge within the project **FREEgreenius**. The executable is available from the website http://freegreenius.dlr.de .

greenius was developed at the German Aerospace Centre (DLR). Rainer Kistner, Winfried Ortmanns, Volker Quaschning, Jürgen Dersch, Simon Dieckmann, and Javier Inigo Labairu belonged to the development team. Development, distribution and service are made under licence of DLR.

This extensive user manual should make it easier to get into **greenius** and gives an overview about the possibilities. Beginning with version 4.3 the manual contains the same information as the online help system which you can start by pressing *F1*. The following symbols have the following meaning:

Menu entry:	example: *File|Exit*	
Key	example: *F12*	
Button	example: *OK*	

In the next section you get information about the first start of **greenius**.

*The **greenius** team thanks you for your interest and hopes that the software can meet your visions.*

Acknowledgements

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Publishing, further development and user support for FREE **greenius** is currently enabled trough funding by the **German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety** based on a resolution of the German Parliament (Funding reference number: 0325427)

The addition of models for solar cooling with concentrating and non-concentrating collectors was funded by the **European Commission** under the 7th Framework Programme (Contract no. TREN/FP7EN/218952)

The addition of models for process heat generation with concentrating and non-concentrating collectors was funded by the **German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety** based on a resolution of the German Parliament (Funding reference number: 0329609A)

The extension of **greenius** for concentrating PV systems was funded by the **European Commission** under the 6 Framework Programme (Contract no. SES6-CT-2003-502626)

The development and implementation of **greenius** started in 1999 and funding was provided by the **European Commission** under the ALTENER II Programme (Contract no. XVII/4.1030/Z/98-268)

The responsibility for the content is on the authors.

Getting Started

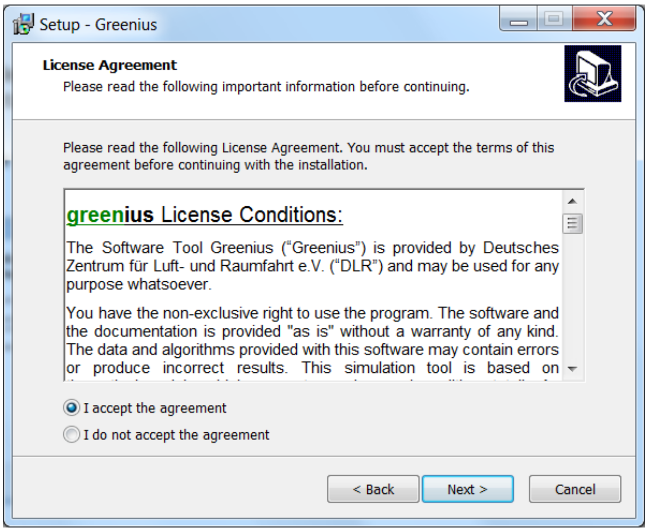
This section gives you an overview of the installation process as well as the simulation of you first simulation project with **greenius**. If you have already installed the software take a look at the project wizard. It leads you through the first steps of the project setup.

Installation

For the use of **greenius** the following minimum operating system and hardware requirements must be fulfilled:

- 32 or 64bit version of MS-Windows (MS-Windows 10 or newer)
- x86bit or x64bit-processor with 1 GHz or faster
- 1 GB RAM
- XGA screen, resolution 1024 x 768px or higher

The **greenius** installer from the Internet page is packed to a ZIP-file. This file must be uncompressed into a temporary dictionary with an unzip program such as 7-Zip or Winzip. Start the **Setup.exe** file and follow the instructions. After successful installation you can start **greenius** by using the desktop icon or the start menu entry.



Important hint: greenius must not necessarily be installed on the system disk (typically named "C:"). Instead, it is recommended to install the software in a separate partition (e.g. "D:") since **greenius** creates a couple of subdirectories for component and project datasets which are modified later on. On current OS versions like Windows 10 or newer the access rights of users on the system are typically restricted and this might cause problems when installing the software on the system disk.

Greenius Licence Conditions

With the installation of **greenius** you automatically must accept the following licence conditions::

The software tool **greenius** ("Software") is provided by Deutsches Zentrum für Luft- und Raumfahrt e.V. ("DLR") in object code to anyone and may be used for any purpose whatsoever.
You have the non-exclusive right to use the program free of charge. The Software and the documentation is provided "as is" without a warranty of any kind. The data and algorithms provided with this Software may contain errors or produce incorrect results. This Software is based on theoretical models, which may not reproduce real conditions totally. As a result, practical results may differ significantly from the simulation results of this Software. The entire risk for the quality and performance of the Software, data and calculation is borne by you.
This Software was successfully tested with the most common Microsoft® Windows operation systems.

However, installing and running new software may produce some difficulties and data losses. Therefore, it is strictly recommended to make a backup of all data and software of your PC before starting the installation. There is no warranty for correct information or the non-existence of subsequent damage of any kind. It is NOT warranted that the functions contained in the software will meet your requirements or that the operation of the Software will be uninterrupted or error free.
You agree that you will not, and will not allow any third party to, (1) sell, license, distribute, transfer, modify, adapt, translate, prepare derivative works from, decompile, reverse engineer, disassemble or otherwise attempt to derive source code from the Software, unless otherwise permitted, (2) take any action to circumvent or defeat the security or content usage rules provided, deployed or enforced by any functionality contained in the Software.
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greenius uses a compilation of parts of the SUNDIALS package from Lawrence Livermore National Laboratory for solving the DAE systems. Therefore each **greenius** installation includes a copy of the SUNDIALS licence according to the rules of this software package (see file “Sundials_licence.txt”).

First Run

After the successful installation of **greenius** you can start the program by clicking the icon on your desktop or by starting the program from the start menu.

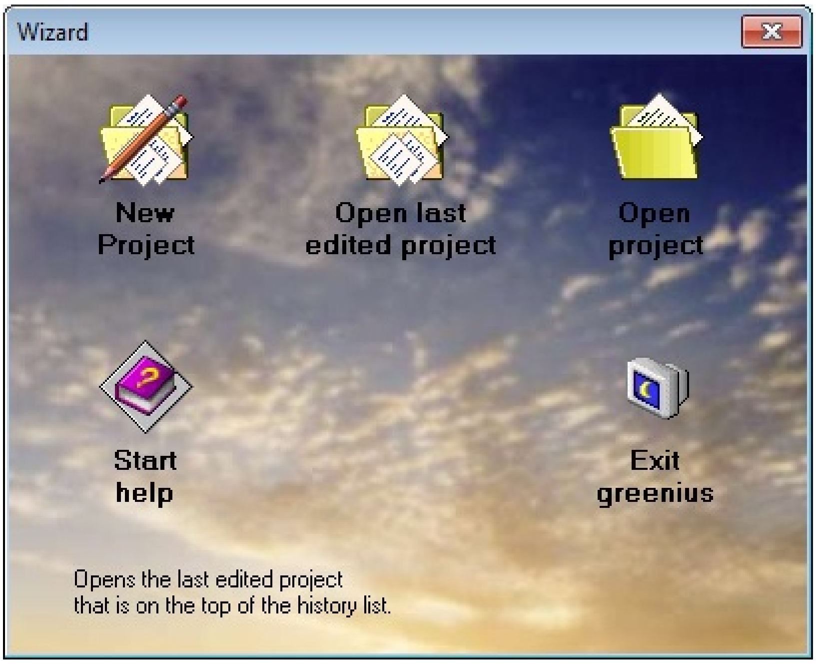
After starting the program the wizard appears automatically. It helps at the creation of new projects or opening of existing projects. **greenius** comes with a couple of Example Projects that can easily be used as base for new individual projects.

As language of the user interface you can choose between German and English. The language can be changed even when the program is running with the menu entry *Language* respectively *Sprache*.

Most charts and tables shown in **greenius** can be copied via the context menu that opens on a right-click. The tables can also be copied or modified using *Strg+C* or *Strg+V*.

Project Wizard

After starting the program the wizard appears automatically. It helps at the creation of new projects or opening of existing projects. With the key ⌨*Esc* you can close the wizard. At the menu entry ■*File|Wizard* respectively key ⌨*F12* you can start the wizard again at any time.



New Project

After choosing a new project at the wizard, you must enter the project name to distinguish between different projects. In the next step you choose the technology. Therefore, the technology selection window starts automatically.

In the next step you must choose a meteorological data file. This is essential for most renewable technologies. This terminates the definition of the new project. Starting from the main screen, the parameters of the project can be changed or a simulation can be started directly with the key ⌨*F9*.

Open Project

With the button *Open Project* you can open existing projects. The default directory for project save files is the `data` subdirectory of the **greenius** installation folder. On the first start you will only find a couple of exemplary projects that have been set up by the developers and show realistic configurations for the different technologies.

You also find the button *Open last edited project* which is self-explanatory and quite useful.

Example Projects

greenius comes with a couple of example projects in order to demonstrate the utilization.

Ebsilon®Professional has been used to calculate power block performance for all these plants [Ste16].

Andasol

Parabolic trough CSP plant with 7.3 hours of thermal storage capacity (2-tank molten salt storage). Technical data chosen similar to those of the Andasol 1 and 2 plant in southern Spain but not representing them exactly because not all details have been disclosed.

Coordinates of the Andasol plants are chosen as site. The plant is asumed to operate in solar only mode without any fuel utilization.

Collector type: Eurothrough 2 with Schott PTR 70 vacuum receivers. Technical data of these receivers according to test results published by NREL in 2009 [Bur09].

Power block: 50 MW wet cooling power block with 38.7% of nominal gross efficiency.

Specific costs according to *The Power to Change: Solar and Wind Cost Reduction Potential to 2025* published by the International Renewable Energy Agency IRENA [IRE16].

Andasol_2014

Parabolic trough CSP plant with the same technical parameters as in the „Andasol“ example project.

The only difference is that Andasol_2014 uses a user defined operating strategy with 4 periods for every day of the year. The periods are defined in a manner that there is no electricity production between 22:00 and 5:00. The variable feed-in tariff is 0.10 €/kWh between 5:00 and 16:00 and a peak tariff of 0.278 €/kWh between 16:00 and 21:00, followed by 1 hour of normal tariff from 21:00 to 22:00. The operating strategies for those 4 periods are defined in a way to maximized electricity production during the peak hours.

This restricted operation scheme leads to a slightly lower annual electricity production (approx. 7 %).

SolarTower_MoltenSalt

Example project for a 150 MW solar tower with molten salt receiver and storage. The example site is Daggett (California). Storage capacity is 2800 MWh (8.1 hours). The power block has an air cooled condenser and a nominal gross efficiency of 43.4%.

Heliostat field performance for the solar tower CSP plants was calculated with the DLR tool HFLCAL [Sch09]. The lookup tables for solar tower fields are valid for several sites and plant sizes, so they may be used also for user defined plants as long as these plants are within the boundaries for the specific lookup table. The boundary values are shown on the solar field form. Extrapolation of the lookup tables outside the boundaries should be avoided.

SolarTower_Air

This project is located in Daggett (California) as well. However, it uses open volumetric receiver technology with air as heat transfer fluid. The power block has a nominal gross output of 53.9 MW at 41.5% efficiency. The single tank storage has a capacity of 650 MWh (5.0 hours) and the receiver delivers 236.8 MW of thermal output at an intercept of 350 MW. Heliostat field performance is calculated with HFLCAL [Sch09] for northern latitudes where the sun's azimuth direction does not reach the range between -60° and + 60° (North is 0°).

Almeria_PV

PV example project with 704 kVA nominal AC power located at Almeria (southern Spain).

Almeria_VTC

Example project for heat production using a vacuum tube (compound parabolic) collector located at Almeria.

Almeria_flat

Example project for heat production using a flat plate collector located at Almeria.

Almeria_Trough

Example project for heat production using a small parabolic trough collector located at Almeria.

Almeria_Fresnel

Example project for heat production using a linear Fresnel collector located at Almeria.

Chiller_VTC

Example project for solar cooling using a vacuum tube (compound parabolic) collector located at Almeria.

Chiller_PT

Example project for solar cooling using a parabolic trough collector located at Almeria.

Parabolic_Trough_150MW

Example project for a 150 MW parabolic trough with molten salt storage located at Daggett.

PV with Battery

Example project for PV with battery located at De Aar.

Hybrid Tower

Example project for solar tower with PV located at De Aar.

Hybrid Trough

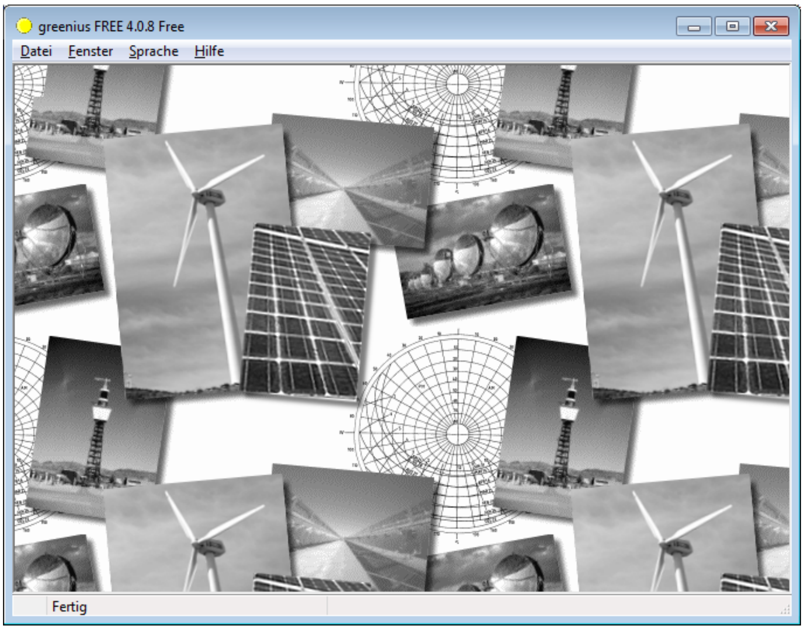
Example project for parabolic trough with PV and electric heater located at De Aar.

Program Description

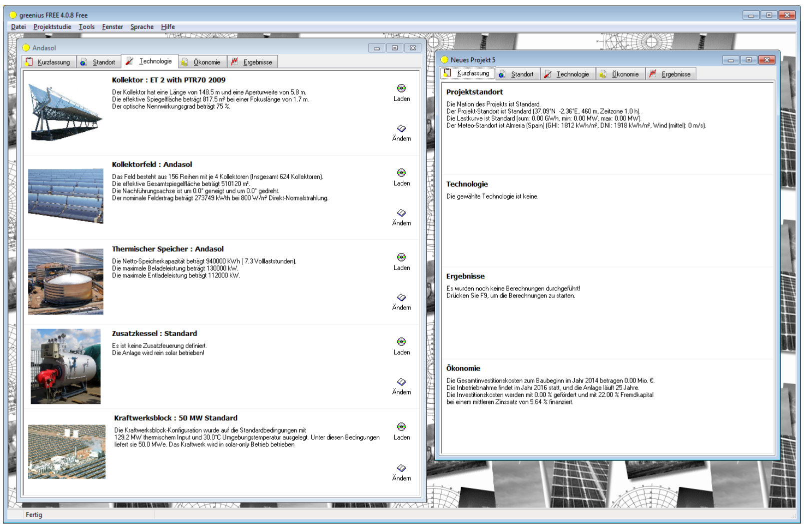
This chapter gives a general overview of the **greenius** user interface, especially the main form and the project form. greenius uses a project structure where each component is saved to a separate file, which allows to use the same component in different projects. The concept is described in the Project Structure section.

Main Window

If no project is open, only the **greenius** main form is visible. It is shown in the picture below.



The main form exists only once and is the frame for all projects that you create or open. As you can see below, a new window is opened for each single project where you find tabs for the different input parameters and the results of this project. There is now individual menu bar in the project window. The menu bar in the main form is therefore always refers to the currently active project. For example by clicking on *File|Save Project* you save only the active project, not all projects. Depending on the windows theme you use the active project window is highlighted differently. In the screenshot below the active project window may be distinguished by its slightly darker frame.



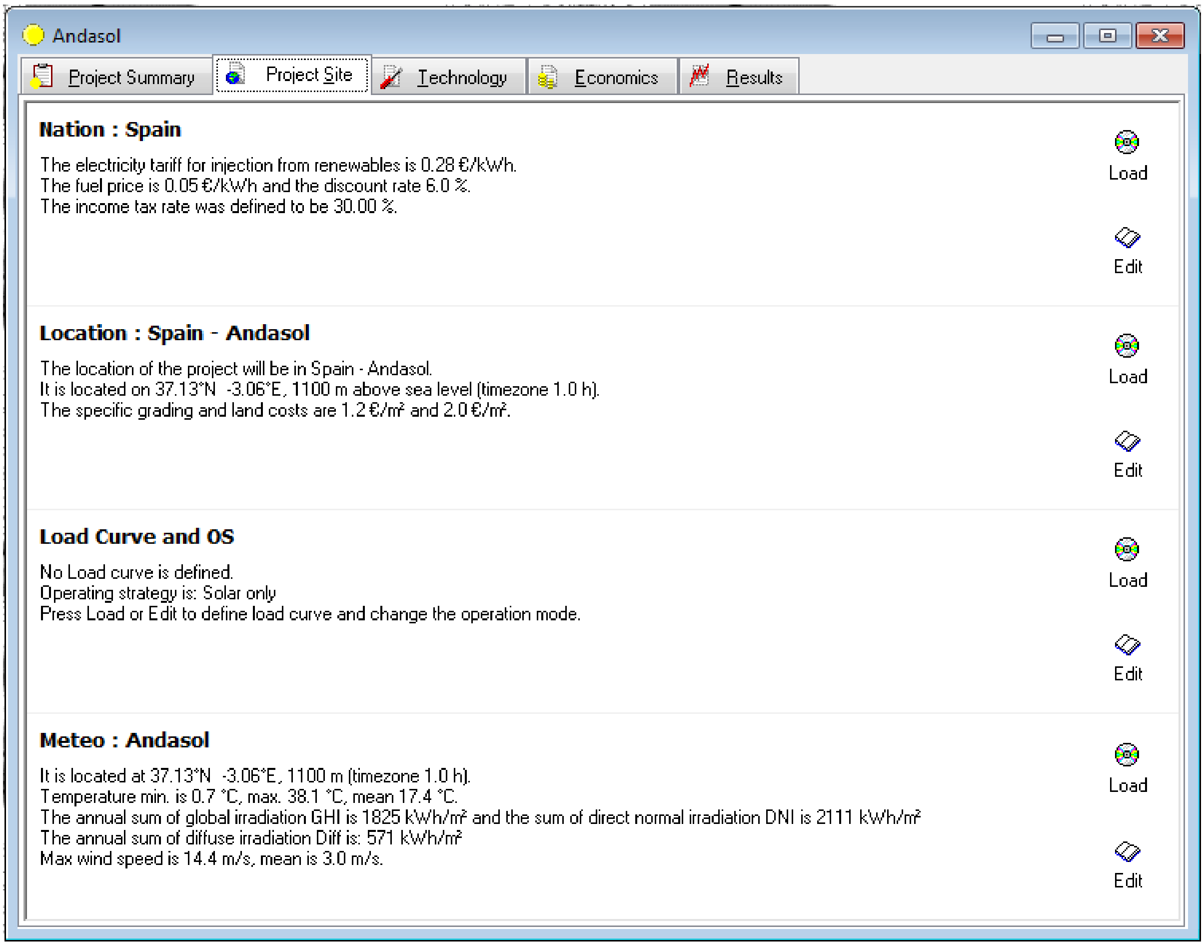
If more than one project is open, you can switch between the projects at the menu entry *Window*. With *Window|Arrange* the windows of all open projects can be displayed simultaneously.

Project Window

The project window consists of five tabs:

- Project Summary
- Project Site
- Technology
- Economics
- Results

The *Project Summary* gives you a condensed summary of all the parameters and results in the other tabs and gives a quick insight into the project. The three tabs Project Site, Technology and Economics contain the input components of the project. Each component is represented by a short summary in the project window and two corresponding buttons: With ↳*Load* a component can be loaded while ↳*Edit* opens the corresponding component window where the parameters can be modified. The components in the *Results* tab have only a ↳*View* button.



Menu Overview

Main Menu

From the main menu of **greenius** you can open all general forms that are used to configure the software itself, to create, open and save projects and to start the simulation. You can also start a couple of tools that may help you with your work in **greenius**. Below you find an overview of all menu entries with links to the corresponding chapters of this manual. Please note that some of the menu entries are not available unless you open a project.

It is also important to notice that some actions from the menu bar (such as *File|Save Project*) apply to a certain project. In these cases the action is always executed for the currently active project which is usually highlighted in some way depending on the display theme you use.

Part 1:

File	Project Case	Tools
New Project	Select Technology...	Shading Editor
Open Project...	Run Calculation...	Visualize...
Close Project	Calculate Economics	
Save Project...	Calculate all Projects	
Save Project as...	Create Copy	
Import Project...	Copy with new Meteo	
Export Project...		
Wizard		
Last open Project A		
Last open Project B		
Last open Project C		
Last open Project D		
Project Info...		
Preferences...		
Exit		

Depending on the number of opened and last saved projects there is a short list of up to four last opened projects at *File.* You can close the active project with *File|Close Project* and exit **greenius** by clicking *File|Exit.*

Part 2:

Window	Language	Help
Arrange...	English	Start Help...
Project X	Deutsch	About...
Project Y		
...		

greenius gives you the possibility to open more than one project at the same time. The menu entry *Window* allows you to switch between all open projects. With the menu entry *Window|Arrange...* you can show all open project windows next to each other in order to get a better overview.

Currently, **greenius** supports only two languages, English and German. You can switch between both under ■*Language* at runtime. This help is opened using ■*Help|Start Help...*, while ■*Help|About...* states the version information of your copy of **greenius**.

Project Structure

The Data Structure of greenius Projects

greenius projects rely on a component structure. A component is for example the *meteorological data* or the *parabolic trough component*. Each of these components can be saved in a separate file that contains all parameters defined for this type of component. Each type of component is by default saved in an separate directory within the **greenius** data structure.

The default data structure starts with the folder `data` in your **greenius** installation directory. For example, if you installed your copy of **greenius** to `D:\Software\Greenius` you will find the data directory structure in `D:\Software\Greenius\data`. If you look at the `data` folder you will find the saved project files and a couple of subdirectories where each one is filled with saved component files of the corresponding type. For example, all PV modules in this example would be saved to `D:\Software\Greenius\data\Technology\PV\Module`.

In general, it is not recommended to change the location of the saved files. However, you can do so by editing the `greenius.ini` in the section `[Directories]` where you find the location of the save folder for each type of component. You should find the `greenius.ini` in the main **greenius** folder.

A whole simulation project is composed of several components that can be loaded and edited in the project window. The project itself is saved directly in the `data` directory. These project save files do not contain the component information themselves, but only relative paths to the component save files of which the project consists. Consequently, if parameters of a component such as a photovoltaic module are changed and saved, these changes are **valid for all projects that use this component file**.

Create Project

You can create a project with ■*File|New Project* which opens a new project structure where all components are set to default. When you click on the *Technology* tab of the project window the Select Technology dialogue opens automatically.

If you want to create a variation of an existing project you can use ■*Project Case|Create Copy* or ■*Project Case|Copy with new Meteo.* The only difference between both is that the *Load Meteo File* dialogue will open automatically if you use the latter option.

Open and Save Projects

With ■*File|Open Project* respectively ■*File|Save Project* a project can be opened or saved. When saving a project, only the file names of the component files are saved in the project file. If the project file shall be copied to and opened on another computer, all belonging components must exist in the relative directories. The import and export functions can help you to transfer whole projects from one to another computer.

Import and Export Projects

To transfer a project with all its components to another computer, the import and export functions can be used (*File|Import Project* respectively *File|Export Project*). When exporting a project all project components and their project information are compressed to a single GPE file. When importing a project all components will be extracted and distributed to the correct subdirectories defined within the **greenius** version you import the project with.

In many cases a project that shall be imported uses component files with the same file names as already existing ones. This is the case for default component files and also widely used common files like cost, timing or financing components.

Whenever a component file name already exists a warning message is issued where you can decide individually or for all component files together what should be done. It is not possible to automatically rename the files. If you want to keep your existing files and import the new components with a new file you have to do that manually with a text editor. Otherwise you may rename the existing file and restart the import process within **greenius**.

It is also not possible to view the differences between the existing file and the one to be imported. Instead you would have to use a text editor with compare functionality to do so. The GPE file contains, one after another, the content of all component files separated by delimiting lines that start with '###'. The delimiting lines at the beginning of each component contains the file name under which it has to be saved. The manual extraction of single components is therefore possible without much effort using a text editor.

For a quick work flow we recommend to never change the files that are distributed together with greenius and use individual file names if any parameter is changed. Then you can **choose 'No all' when asked for overwriting existing files** and the project you import will use the already existing files. Following this advice you do not run into the risk of unintentionally replacing component files which are used in other, already existing projects!

Data File Syntax

In **greenius** components and projects are in general saved in one of the two available file formats: ASCII (`*.gpa` or `*.gpj`) and binary (`*.gpd`). The recommended format is the ASCII format. The component ASCII files use the file name extension `*.gpa`, the project files `*.gpj`.

Component File Structure

The ASCII component file structure is quite simple and easy to edit. You can modify the files with a standard text file editor. Usually, one parameter is stored per line in the form:

```
parameter_Name  <Tab><Tab>  value
```

greenius uses the colon '.' as decimal separator, but it interpretes also commas as decimal separator. Consequently, it is not allowed to use thousands separators of any kind. It is not obligatory to use a double <Tab> between parameter name and value. a simple blank works as well.

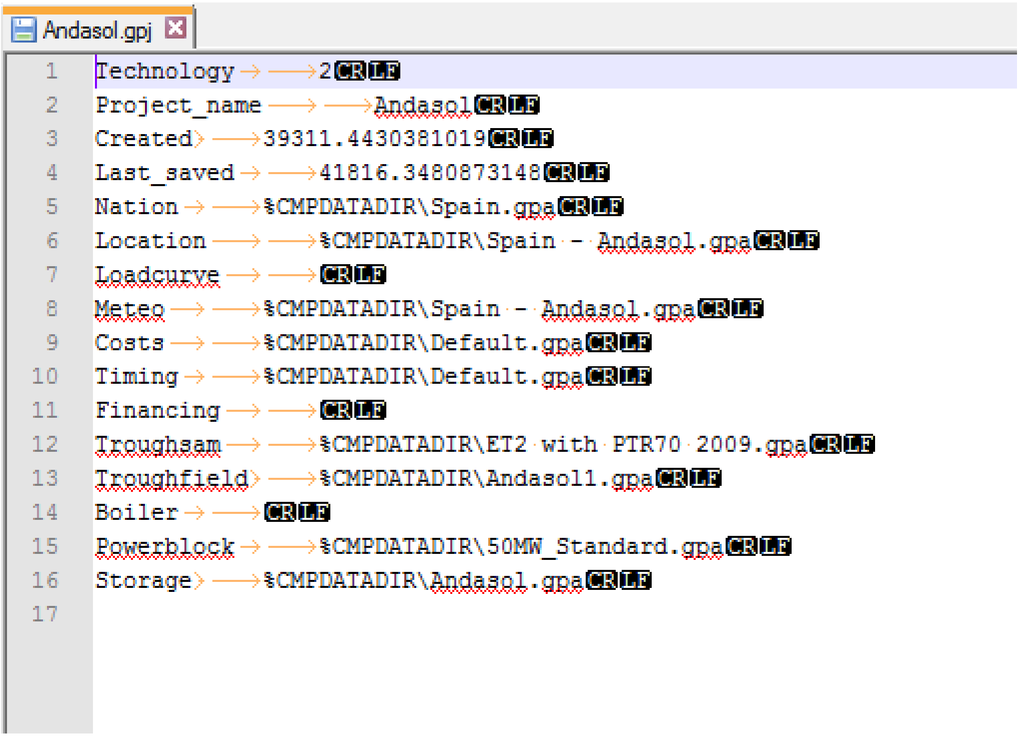
Below you can see an example of a PV module file. Please be aware of the fact that some components use parameters in form of matrices, e.g. the power block, or arrays. In those cases the file structure is slightly different. Mostly, array values will be saved in one line separated by a <Tab>, matrices are written with one row or column per line starting in the line after the parameter name and also use `<Tab>` as value separator. Refer to the corresponding sections of this manual to read more about the specific file structure of the component you are working on.

Schott Perform Poly 250.gpa

```
name	Schott Perform Poly 250
source	Schott Datasheet 2012
contact	greenius Team
nominal_power	250
nominal_voltage	30.8
nominal_current	8.12
OC_voltage	37.9
SC_current	8.66
fill_factor	0.762
nominal_efficiency	0.153
length	1.652
width	0.99
area	1.63548
weight	20
eff_coeff_a1	0.153
eff_coeff_a2	0.013954
eff_coeff_a3	0
alpha_power	-0.0045
alpha_voltage	-0.0033
alpha_current	0.0004
cell_type	2
concentrator	0
nominal_irradiance	1000
nominal_temperature	25
concentration_ratio	1
profilfactor	1
const_temp	1
cell_temp	25
spec_parasitics	0
heat_transcoeff	0
```

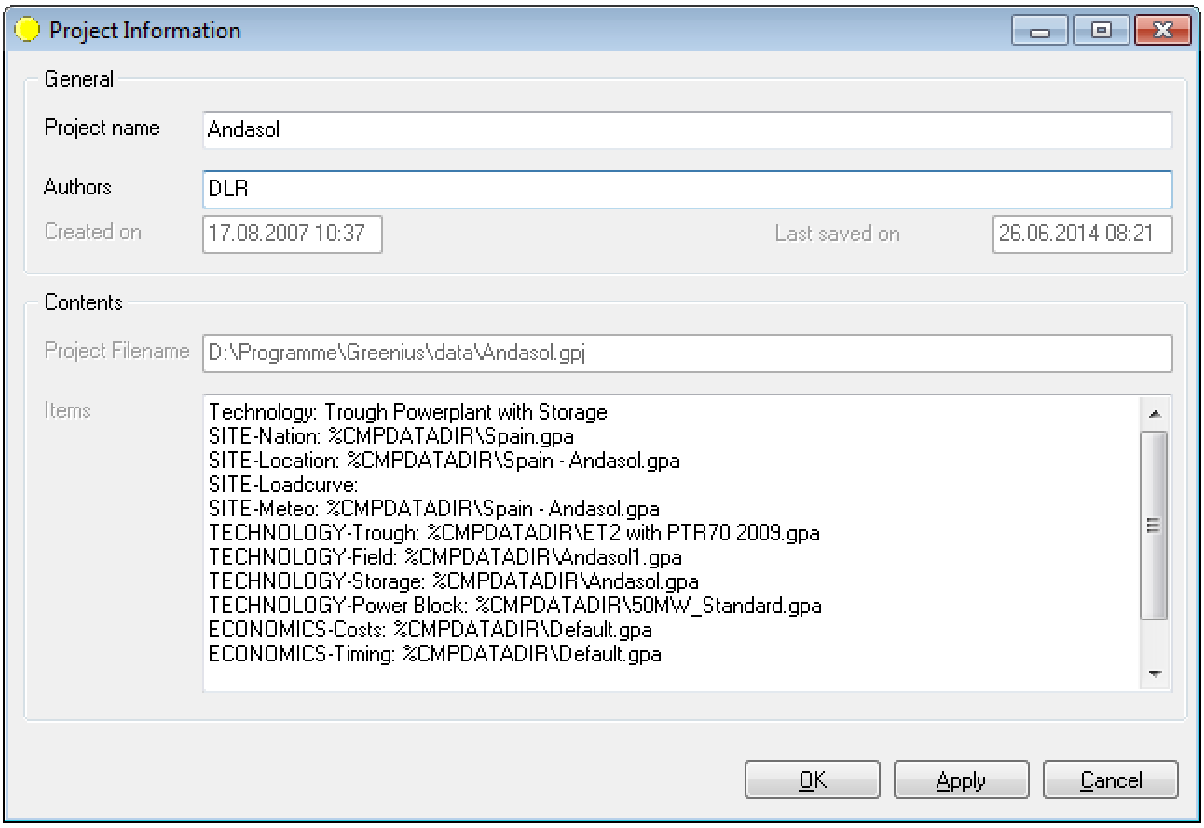
Project File Structure

Project files (*.gpj) look similar to component files and use the same syntax. In the example below four standard parameters are stored: *Technology*, *project name*, *create* and *save date*. Starting with line five the components of the projects are defined by references to their files. Note the usage of the identifier `%CMPDATADIR` which is automatically replaced with the corresponding component directory. For example, the Parameter *Nation* is set to `%CMPDATADIR\Spain.gpa`. The corresponding component directory is `..\Greenius\data\Site\Nation`. Consequently, **greenius** loads the file Spain.gpa in this subdirectory. The identifier %CMPDATADIR refers to a different sub directory for each component type. This is why the same identifier can be used even though the component files are stored in a different sub directory for each component type. The component sub directories can be changed even though this is not recommended.



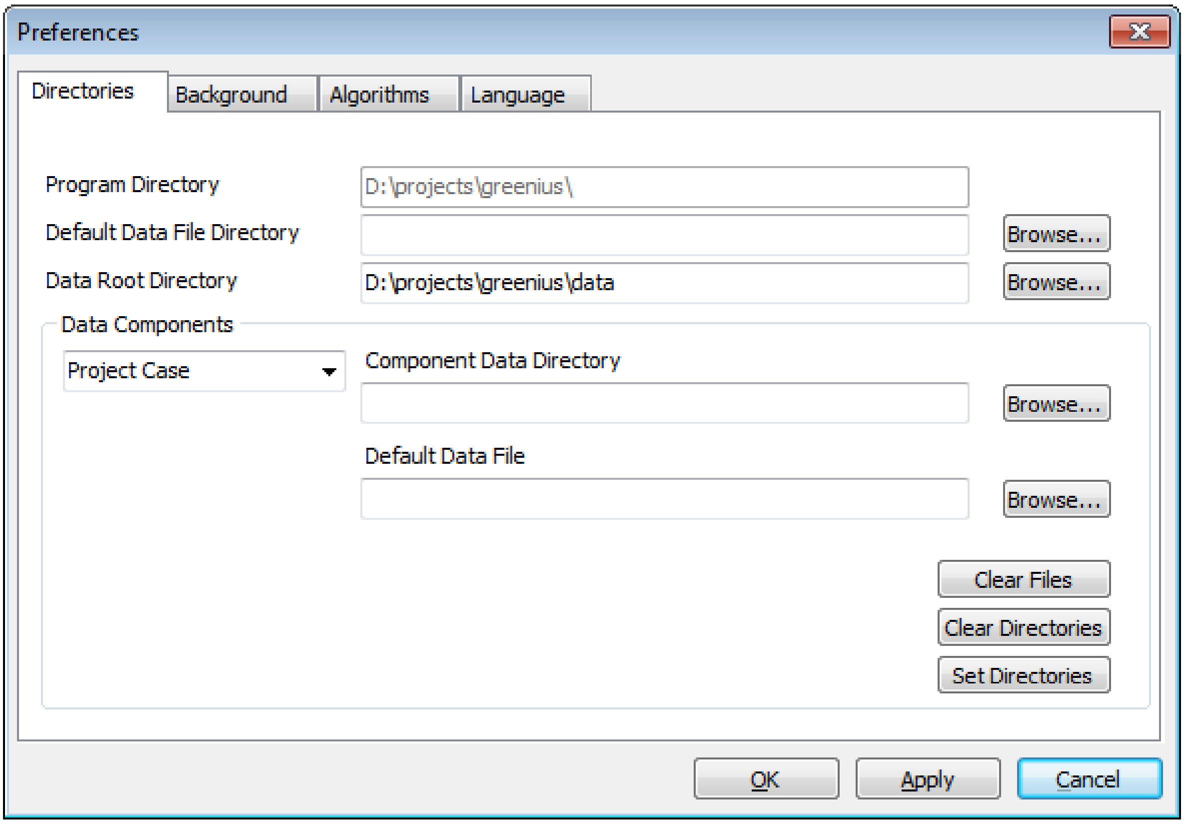
Project Info

The menu entry *File|Project Info* opens the project info window. This window contains information such as the project name, the date of the last saving, and the file names of all project components (see also Project File Syntax). Standard component directories are marked with %CMPDATADIR.



Preferences

The menu entry *File|Preferences* opens the preferences window. All preferences are saved when exiting **greenius** and are available again at the next program start.



Directories	Here you find all default data directories and files which are used by **greenius**. By default several subfolders of the folder `data` in the greenius main directory are used. In most cases it is not necessary to change those settings.
Background	Here you may define an individual background picture for the main screen.
Algorithms	Various algorithms for the calculation of the position of the sun and diffuse irradiance models can be changed here.
Language	The language of the user interface can be changed here. Currently German and English are available.

Components

Every project consists of different components. These components are subdivided into three categories:

- Site
- Technology
- Economics

Site

The components in the category site exist in every project even though some specific parameters may be used only for certain technologies. The four components in this category are:

- Nation
- Location
- Load Curve and Operating Strategy
- Meteorology

Technology

There are numerous different components in the technology category. Whether they are used in a project depends on the chosen technology type. Below you find an overview of all components. Be aware of the fact that for parabolic trough and non-concentrating solar collectors you can choose between different types of operation (e.b. process heat vs. electricity generation). You find more information on the components of each technology in the technology type selection section.

Parabolic Troughs

- Trough Collector
- Trough Field
- Thermal Storage
- Auxiliary Boiler
- Power Block
- Two-Stage Chiller (for chilling projects)

Power Tower

- Tower Field
- Tower Receiver
- Thermal Storage
- Power Block

Dish-Stirling

- Dish-Stirling System

Process Heat according to ISO 24194

- Solar Collector
- Solar Collector Field
- One-Stage Chiller (for chilling projects)

Photovoltaic

- PV Module

- PV Inverter
- Grid-Connected PV System
- Concentrator

Wind Power

- Wind Converter
- Wind Park

Fuel Cells

- Fuel Cell
- Hot Water Storage

Economics

The components in the economics section remain the same for all projects.

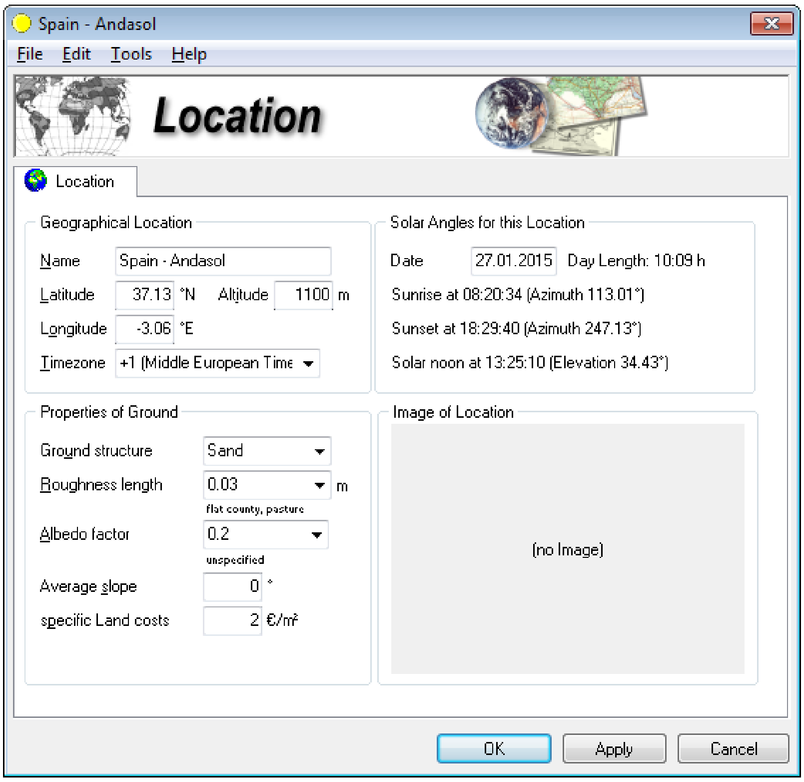
•Costs

•Timing

•Financing

Component Windows

All component windows have identical menu entries. Some components have also additional menu entries. As well, the buttons *OK*, *Apply*, and *Cancel* exist in each component window and have the same functionality.



With *File|Load* respectively *File|Save* and *File|Save As* the component file can be loaded or saved. The standard component directory is used as default directory. You can change the directory, but this is not recommended because **greenius** will not find the component when opening a project with relatively defined file names.

The menu entries *File*|*Apply*, *File*|*Close and cancel* and *File*|*Close and apply* are identical with the buttons *Apply*, *Cancel* and *OK*, respectively. The key *ESC* also closes the window and rejects component data changes. Please be aware, that *Cancel* does only reject those data changes which have been made since the last hit of the *Apply* button (it has no "Undo functionality").

The menu entry *Edit*|*Load Default Values* opens the component file that is defined as standard component. The menu entry *Edit*|*Set File as Default* replaces the default component by the current component file. Every time a new project with this type of component is created this file is automatically loaded.

For most component parameters there is a range check. Non-plausible values are marked in red. However, simulation runs can be also performed with red marked values.

All components contain a parameter *Name* which must not necessarily be the same as the file name. Nevertheless, it is usually recommended to use the component name also as file name.

Site

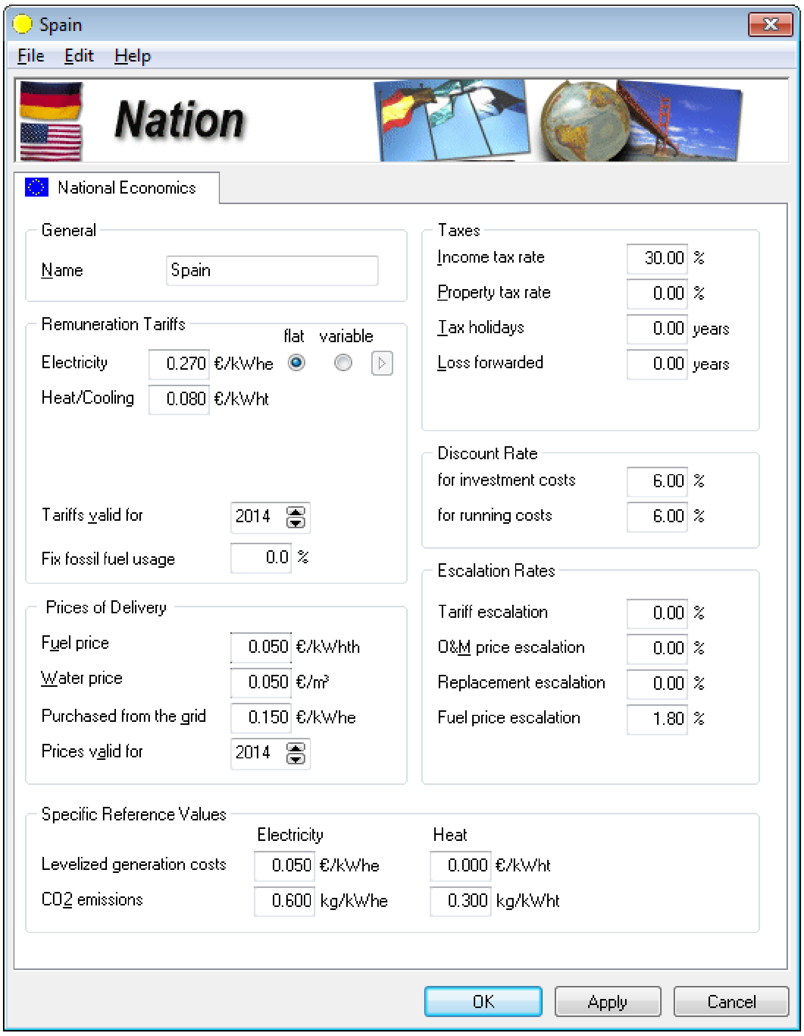
The Site consists of the following components:

- Nation
- Location
- Load Curve and Operating Strategy
- Meteo

Nation

The nation window contains general country information, which is usually independent from the location inside the country. In detail the following parameters are defined here:

- Remuneration Tariffs
- Allowed fossil fuel usage (as a fixed maximum percentage)
- Prices of Delivery (e.g. for fuels)
- Taxes
- Discount Rate for further calculation of the electricity and heat generation costs
- Price Escalation Rates
- Conventional Specific Reference Values



The remuneration tariffs can be fix or variable. When choosing variable tariffs the tariff generator is opened with the triangle button. Different remuneration tariffs for every hour of the year can be defined there. When simulating solar chillers, the given remuneration tariff for heat is used for the economical evaluation of the cooling power!

The fixed fossil fuel usage parameter is **only applied for parabolic trough projects with electricity generation**. When a fixed fossil fuel usage is given in the Nation form, **greenius** does a post-processing of the simulation results. The typical operation year is simulated based on a solar-only operation and the user-defined fraction of fossil fuel usage is added on top of the gross solar electricity generation considering the given percentage in the nation form. The total net electrical output is calculated assuming the nominal plant net/gross efficiency for the conversion of fossil heat. A fuel to heat conversion efficiency is not explicitly considered, which means that the fossil fuel usage given here is based on heat inputs.

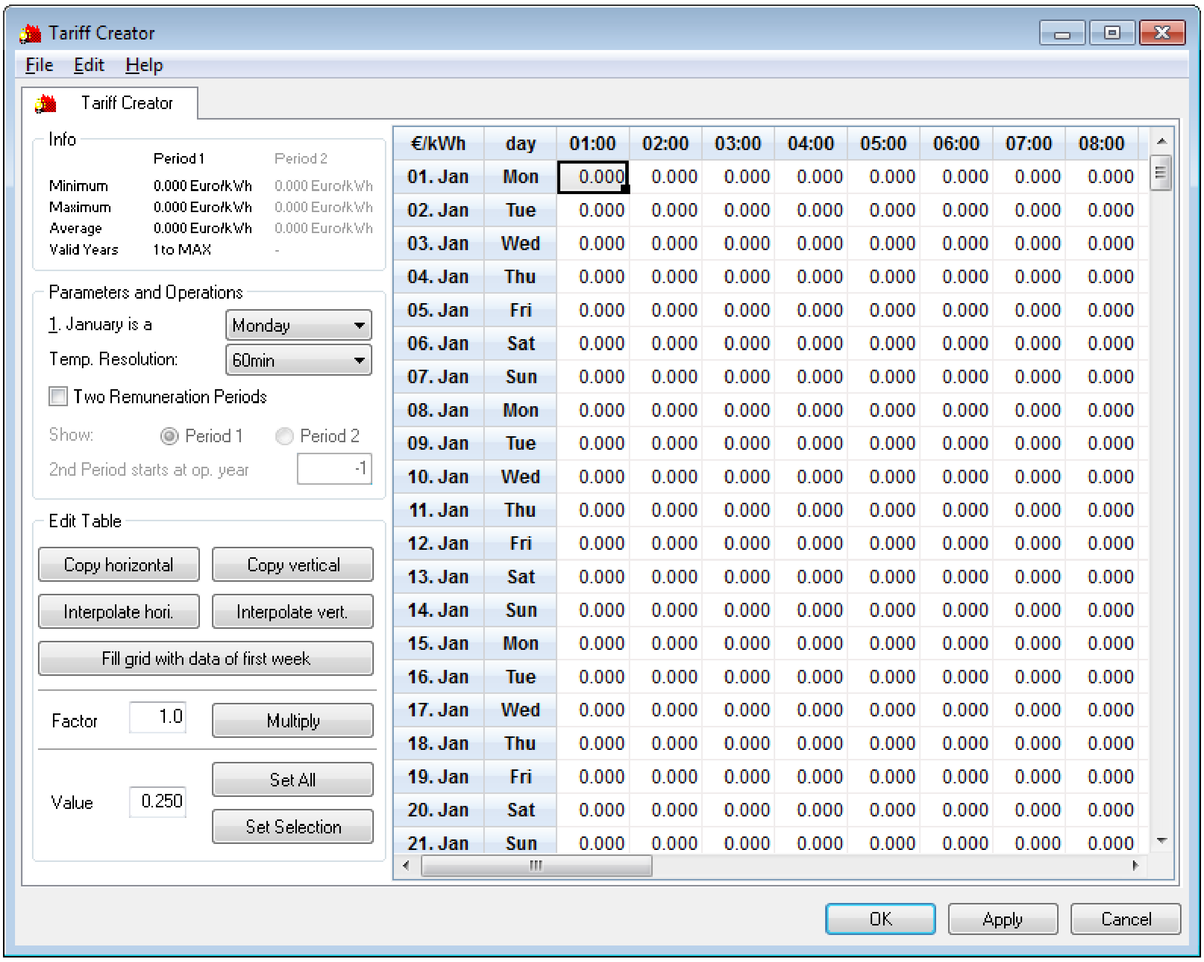
$$x_{fossil} = \frac{Q_{fossil}}{Q_{solar} + Q_{fossil}}$$

The fixed fossil fuel usage option cannot be used together with the load curve **requiring a certain electrical output for each hour**! **greenius** will display a warning if the user tries to use both options together in the same project.

The conventional reference values are the basis for the later calculation of the carbon dioxide avoidance costs. If these calculations shall be reliable, these parameters have to be chosen carefully.

Tariff Generator

The tariff creator form is used to define variable remuneration tariffs for each time step of the simulation. It is opened with the triangle button next to the tariff radio button in the Nation form.



The remuneration data is given using a table where each cell can be edited individually. It is strongly recommended to use the editing functions provided in the lower left box in order to fasten the process. Data can also be pasted from other software via the clipboard using *Ctrl+V* or *Edit|Paste.*

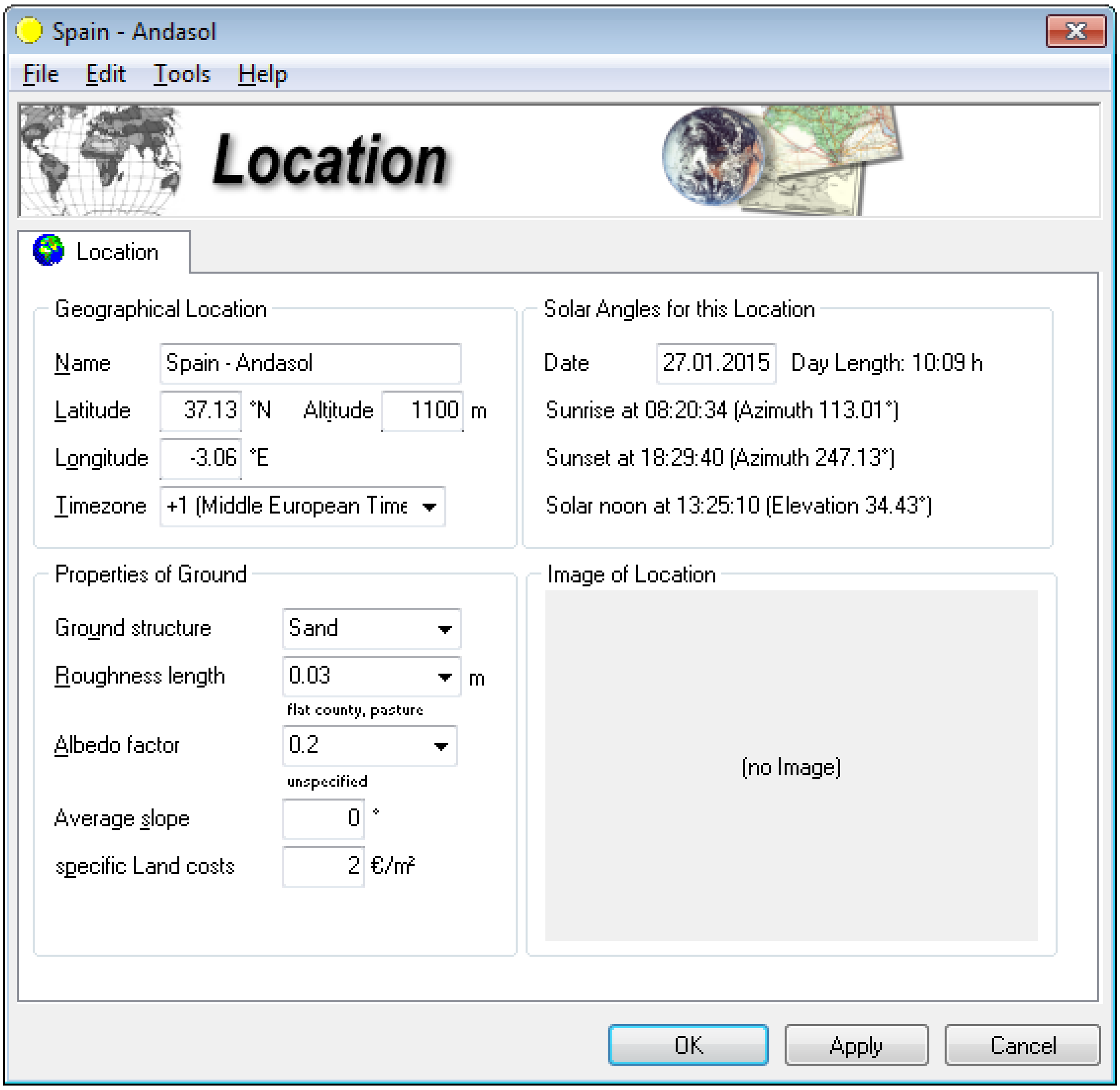
The box *Parameters and Operations* allows to choose the *weekday* of 1st of January which does actually not influence the result of the simulation. The *temporal resolution* can also be changed. Some remuneration schemes may offer increased remunerations during the first couple of years of operation. **greenius** offers the possibility to account for this by defining two different periods for the remuneration tariff. The year where the tariff is switched from period one to period two can be defined by the user. If you would like to use two periods, just check the corresponding check box. The *Info* box above allows the control of the entered values.

Location

The location contains geographical data and ground structure data for the project site. Latitude, longitude and time zone are the reference for all sun position calculations. Therefore, they should be chosen carefully.

Roughness length and ground structure have a large influence on the wind park yield. This parameter is used to estimate the wind speed in hub height on the basis of the wind speed in reference measurement height. If the roughness length is chosen too high, the wind resources will be overestimated. If there are any doubts on the roughness length values, relatively small values should be chosen.

The location window contains also calculation options for sunrise, sunset and solar noon for a user-defined day. The definition of the day and the resulting calculations are only for information and have no influence on later simulations.

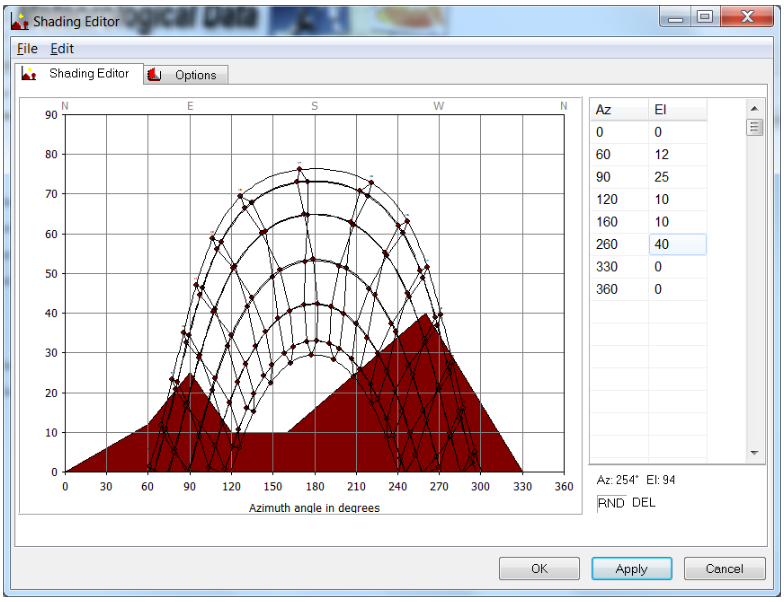


Shading Editor

greenius offers a powerful shading editor that can also draw solar position diagrams. The shading editor can be started via the menu entry *Tools|Shading Editor* which you find in the *Location* component window as well as in the main window. The values for the horizon line can be added manually in the table on the right-hand side or by clicking into the solar position diagram. You can delete points of the horizon line by activating the *DEL* button in the bottom right corner. Here you will also find the *RND* button which activates or deactivates rounding of the angle values. When editing manually the table, be aware of the following requirements:

- The first coordinates must be (0,0)
- The last coordinates must be (360,0)
- The azimuth values must be sorted in ascending order

The data can also be imported from a Horizon-file (`*.hor`). In the Horizon-format south is zero degrees, whereas it is 180° in **greenius**. The azimuth values are adapted automatically during the import. Shading values can also be copied from an into the table via the clipboard.



In the *Options* tab the graphic can be designed individually. The graphic can be copied via the clipboard to other applications or can be saved in common graphic formats.

The horizon data are saved together with the other location data and are used for the simulation of solar systems.

Load Curve and Operating Strategy

This component allows to define a load curve as well as an operating strategy. Due to the strong dependency of the operating strategy on the load curve both are put together into one component. Please refer to the subsections for more information.

A tab with the tariff period is included for the following systems:

- Trough powerplant with storage

- Power tower system

- Grid connected photovoltaic system

- Power tower with fluctuating el. source

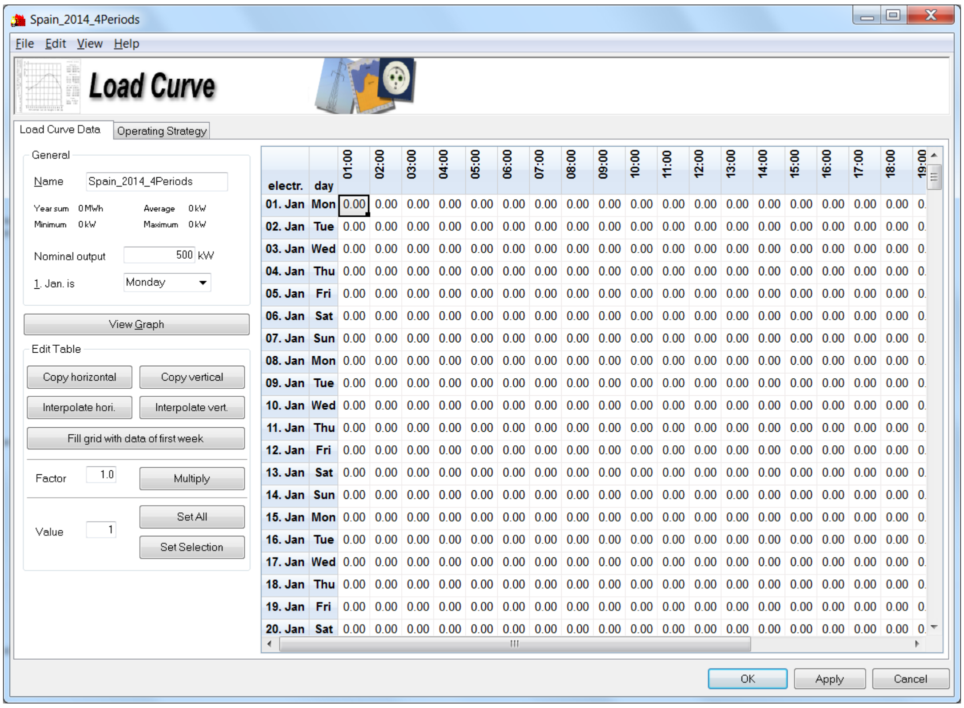
- Parabolic trough with fluctuating el. source

Load Curve

The load curve defines an hourly demand curve which **greenius** tries to follow with the defined system. The demand curve can define all possible forms of output that are available in **greenius** - electricity, heat and cooling power For every time step of the year a different power can be defined. The input data can be displayed graphically by using the button *View Graph*. Data and graphics can be copied via clipboard to other applications.

The load for each time step must be defined as ratio of the nominal output, which is defined on the left-hand side of the form. This procedure eases the reusability of predefined load curves for other projects with a different nominal output but the same characteristic.

The definition of a load curve is optional. If all load curve values are zero, the solar power plant will operate in the default mode, which is called "solar only". In this mode the plant uses as much solar heat as possible in each time step (regardless whether the heat comes directly from the solar field or from the thermal storage).



To simplify the load curve creation, there are some help functions that can be started in the menu entry *Edit* or with the corresponding buttons:

Copy horizontal: If you select several coherent cells in horizontal direction and press this button, the value in the leftmost cell is copied to all other selected cells.

Copy vertical: If you select several coherent cells in vertical direction and press this button, the value in the uppermost cell is copied to all other selected cells.

Interpolate horizontal: If you select several coherent cells in horizontal direction the cells in between the first and the last cell are filled with linearly interpolated values.

Interpolate vertical: If you select several coherent cells in vertical direction the cells in between the first and the last cell are filled with linearly interpolated values.

Fill grid with data of the first week: This button may be used to copy the data of the first seven rows to the whole year.

Multiply: You may select a group of cells and multiply the values by the *factor*. Selection of the whole table can be done by clicking on the cell in the upper left corner as in other spreadsheet software.

Set all: All cells in the table are set to the given value.

Set selection: All cells of the selected area are set to the given value.

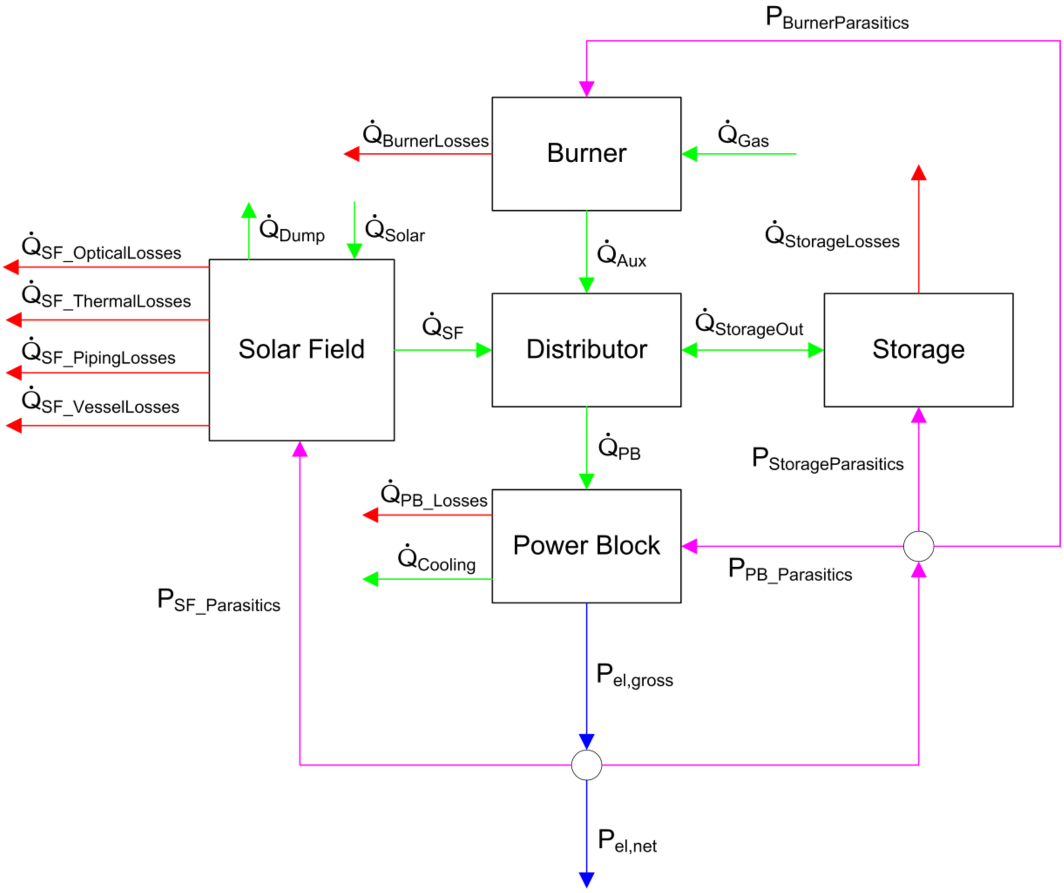
For most renewable technologies the load is only a reference value that is displayed in the calculations. Without storage or backup power plant, PV or wind parks are not able to meet the power demand. Though, for solar thermal trough power plants in hybrid mode and/or with storage the load curve is important. During time periods when heat from the solar field is higher than the heat demand of the power block to produce the required net electricity output, the surplus heat is used to charge the storage. If the heat from solar field is not sufficient, it will be supplemented by heat from storage or auxiliary fossil heater. In case that all three heat sources together cannot deliver sufficient heat, there will be a gap between demand and actual electricity production. If the heat from solar field is higher than the heat demand required to fulfil the load and the storage is completely full, parts of the solar field must be defocused. The potential heat which could be produced by the solar field but cannot be used is summed up as "dumping". Dumping can also occur for PV and wind plants when the potential production is higher than the demand. Note that the operation of a parabolic trough power plant may deviate from the explanations above because of a different operating strategy defined by the user.

The load curve may also be defined for process heat applications.

Operating Strategy

The user defined operating strategy allows control of the operating state of the plant for every simulation time step. **Currently it is only implemented for trough power plants**. Combination with a given load curve is possible.

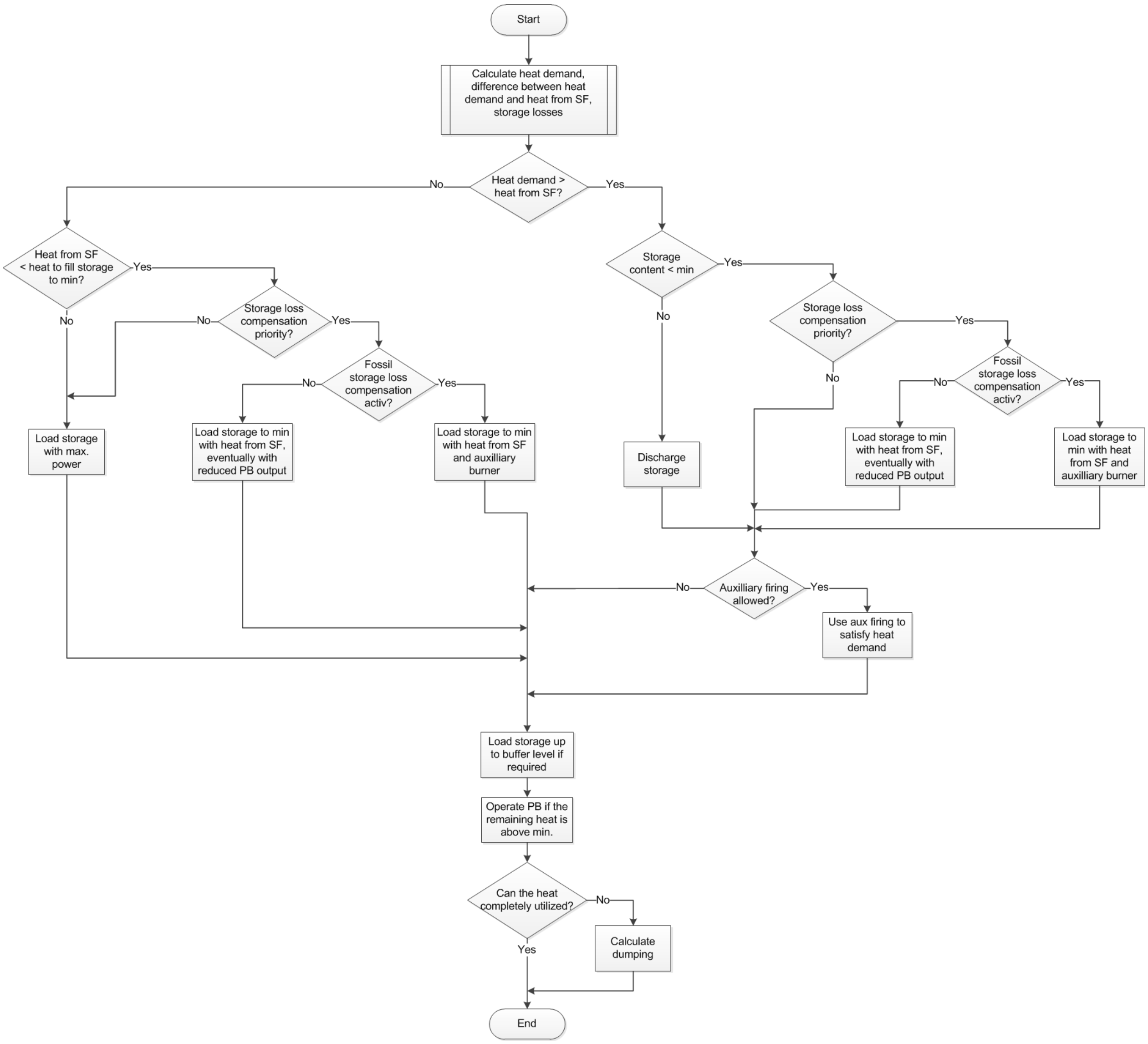
The trough power plant model is based on the exchange of heat flows and electrical power as shown below. Useful heat flows are shown in green and heat losses are shown in red. The useful electric power is marked blue, whereas the parasitic power loss is marked magenta.



The distributor represents the central control element. By controlling heat flows to and from the distributor, the operating state of the plant can be adapted to several requirements (e.g. achieving the highest yield). For the definition of operating strategies, the most important heat flows are from the burner to the distributor and between the storage and the distributor.

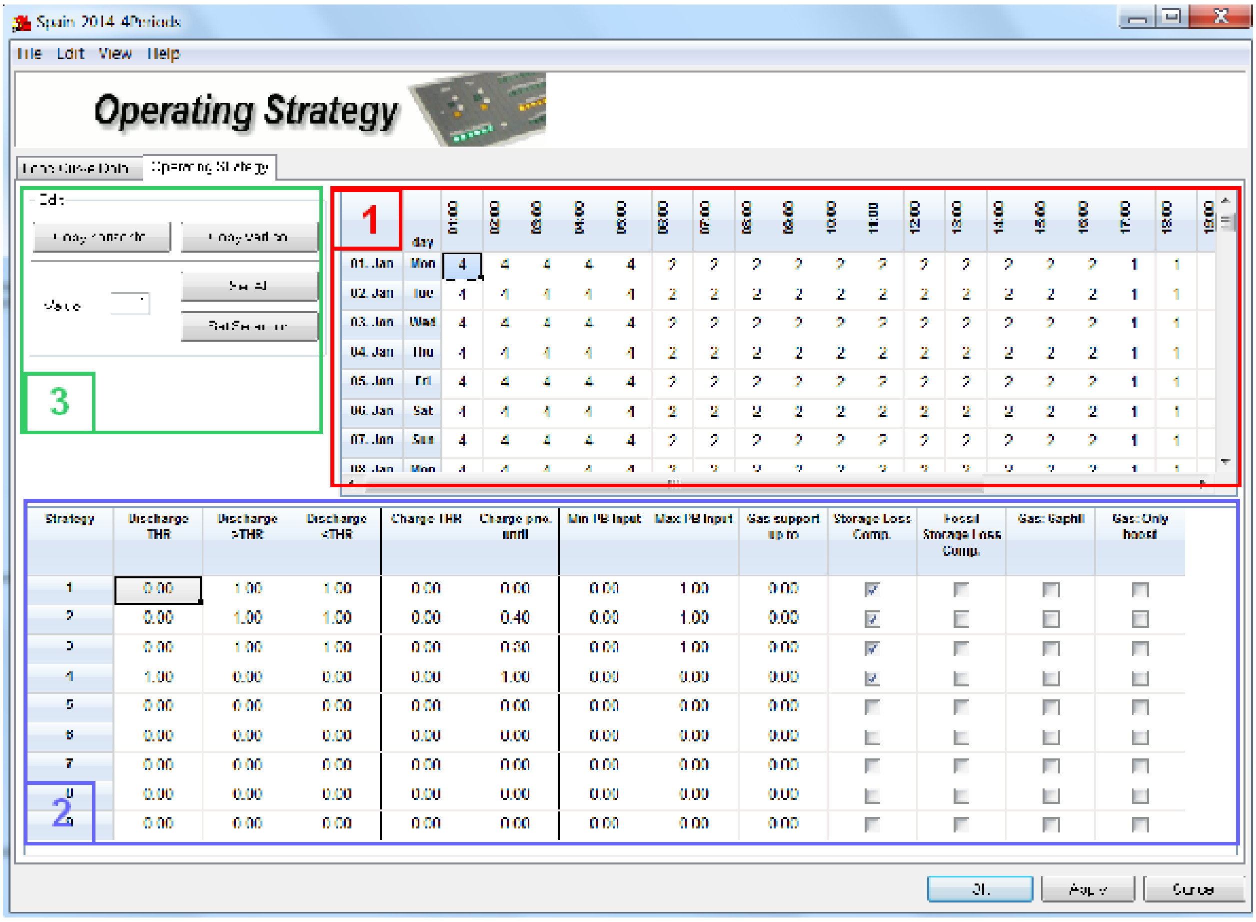
The determination of individual heat flows is performed as shown in the following figure. Initially, the heat demand is determined. If a load curve is defined, the specified demand is taken. Otherwise, the demand is set to full-load. The storage losses are taken into account next. Depending on whether the solar field can deliver the needed energy or not, either the left or the right branch is used. If the solar field delivers sufficient energy the left branch is used. When the storage has free capacity and the operating parameters allow for storage charging, the storage is charged.

If there is not enough solar heat to fulfill the demand, the right branch is passed. Depending on the charge state and the storage control parameters, the storage is discharged or charged to compensate the storage losses. If fossil heat is available, the heat to the power block is increased from this source. In the next step, the storage is loaded to its buffer level in a privileged manner if the specified parameter is set. As long as the storage is loaded to its buffer level, the power block is not operated. In the following step the power block load is set to zero, when the useable heat to the power block falls below its minimum input. The last step is to dump the solar energy which cannot be used by the storage or the power block.



Parameters of the operating strategy

The operating strategy for every hour of the year can be defined by several parameters as shown in the figure below.



In table (1) a certain strategy is assigned to every time step of the year by using a strategy number between 1 and 9. To simplify the assignment of the hours to the periods some of the load curve editing functions were also implemented in (3). For a description, please refer to the load curve section.

The operating strategies themselves are defined in table (2) by modifying the parameters. All numerical parameters in (2) are fractions of the corresponding nominal value, if no other description is given. This ensures the portability of the operating strategies. A description of the parameters is given below:

Columns 2 – 4 in (2) are used to define whether and to which extend the storage can be discharged.

Storage discharge threshold (Discharge THR)

This value is the threshold for the following two storage dispatch fractions. For technology types with power block it refers to the maximal thermal input the power block can accept under nominal conditions. (Discharge THR = 0.5 means: the threshold is 50% of the power block nominal heat input.) For photovoltaic technologies the storage discharge threshold refers to the nominal AC output of the PV system.

Depending on the heat actually delivered by the solar field in the current time instance, the additional heat taken from the storage may be limited to different fractions defined by the following two columns. Therefore the parameters given in columns 2-4 of (2) are used in conjunction.

The valid range for the storage dispatch threshold is 0 to the solar multiple of the field.

Storage discharge fraction for high solar field outputs (Discharge > THR)

This factor refers to the maximal storage discharge power. If the actual heat from the solar field is greater than "**Discharge THR**", the maximal storage discharge is limited by this fraction. The valid range for this fraction is 0 to 1.

This parameter might be used for example to utilize heat from the storage to run the power block at full load when the solar field delivers high outputs.

Storage discharge fraction for low solar field outputs (Discharge < THR)

This fraction refers to the maximal storage discharge. If the actual heat from the solar field is smaller or equal to "**Discharge THR**", the maximal storage discharge is limited by this fraction. The valid range for this fraction is 0 to 1.

This parameter can be used for example to limit the storage discharge during nighttime in summer to allow a 24h operation of the power block.

Examples for the utilization storage discharge THR and fractions:

Discharge THR	Discharge > THR	Discharge ≤ THR	Explanation
0.0	1.0	1.0	Storage discharge is not limited by the OS (default values)
0.0	0.0	0.4	Heat from storage is used only when the solar field does not deliver any heat and the storage discharge is limited to 40% of the maximal storage discharge defined on the storage form. **Goal: extend the storage content in order to run the PB as long as possible.**
0.8	1.0	0.0	As long as the solar field delivers less heat than 80% of the power block maximal heat input (at design conditions) no heat from the storage is discharged. **Goal: Stored heat is only used when the power block could run at high load even without the storage heat, in order to maxi-mize PB efficiency.**

Columns 5 and 6 of (2) are used to define the storage charging. By using these two parameters it is possible to define a threshold above which the exceeding production of the main energy source is fed to the storage until the storage reaches the defined buffer level.

Storage buffer threshold (Charge THR)

The *storage buffer threshold* defines a power threshold based on the main consumer, which must be passed by the main energy source (e.g. solar field), before the priority charging of the storage can start. The value given by the user defines a fraction of the nominal energy demand of the main consumer. The main consumer is the power block respectively chiller if existent. Otherwise the nominal load value defined in the load profile is used. If there is neither power block nor chiller and also no load defined the storage would usually not be used at all. If you want to charge the storage for any reason, try to set the *storage buffer threshold* to zero. Please be aware that you can get storage content fluctuations.

When *storage buffer threshold* is set to 0, the storage buffer level is applied always. When it is set to 1 the storage buffer level priority is disabled. The valid range for this fraction is 0 to the solar multiple of the field.

Storage buffer level (Charge prio. until)

This fraction refers to the net capacity of the storage. It describes to which level the storage is filled up with the first priority. The valid range for this fraction is 0 to 1. By using this parameter the storage can be filled to a certain level before the power block starts. Fluctuations of solar heat delivered by the solar field can be balanced in a better way and the number of turbine starts may be reduced by defining a certain storage buffer level and charge the storage up to this level prior to power block startup. Please be aware of the existence of the parameter *storage buffer threshold* described above which defines an energy threshold below which the priority charging is prevented.

For photovoltaic technologies the parameter works in the same manner.

Columns 7 to 9 of (2) define the power block, chiller or similar component behaviour. **They have no influence if neither of those components exists**.

Min PB Input

This fraction refers to the maximal power block input. It describes the minimum heat input at which the power block starts during the relevant period. The valid range for this fraction is 0 to 1. If this parameter is set to 1 the power block starts only when the available heat (from SF, storage and auxiliary heater) is sufficient to run the power block at full load.

Max PB Input

This fraction refers to the maximal power block input. It limits the maximal power block heat input during the period. The valid range for this fraction is 0 to 1. Setting this parameter to values below 1 restricts the power block load and extends the number of operating hours from the storage.

Gas support up to

This fraction applies to the nominal demand of the main energy consumer. For example, if thermal energy inputs from solar field and storage are not sufficient to fulfil the energy demand of the power block, the thermal energy input of the power block in the current time step is increased by firing gas until the thermal energy input is equal to the product of "Gas Fill Fraction" and maximal accepted thermal energy of the power block. The valid range of the gas fill fraction is 0 to 1. This parameter works also for technologies without power block or chiller, if a load curve is defined.

When this fraction is set to a low value (e.g. the minimum of the thermal input needed to operate the power block), the number of turbine starts can be reduced.

The *Gas Fill Fraction* works together with the two checkboxes *Gas: Gapfill* and *Gas: OnlyBoost*. Those two can be used to apply additional restrictions for the usage of the fossil boiler.

The check boxes in columns 10 and 11 of (2) define the handling of thermal storage losses.

Storage Loss Compensation

The 2-tank molten salt storage has constant losses independent of the load status, the electric storage is also subject to losses at minimum content level. The compensation of these losses has the highest priority if this box is checked. In this case the storage is filled up to its minimum (defined in the storage input window) with solar thermal energy even though the solar thermal energy does not exceed the thermal energy demand of the power block. If it is not checked, the power block has a higher priority and the storage is only filled up if the solar thermal energy exceeds the thermal energy demand.

Fossil Storage Loss Compensation

If this box is checked, the storage is filled up to minimum by using gas, when the solar thermal energy is below the thermal energy demand. This might be useful when the legislation allows fossil fuel utilization only for storage loss compensation.

The check boxes in columns 12 and 13 of (2) give the possibility to define the usage of the fossil boiler.

Gas: Gapfill

If this box is checked, gas is only used when gross electricity generation from solar heat of the preceding hour was greater than zero. This parameter can be used to back up the heat input of the power block in case the solar heat drops below the minimal input of the power block after the power block has been started.

Gas: Only boost

If this box is checked, gas is only used to increase the output of the power block when it could also be operated even without gas utilization. This parameter can be used to increase power block load to achieve a higher yearly thermal efficiency and to prevent fossil-only operation.

Syntax of the Load Curve Component File

The parameters of the operating strategy can be saved to an ASCII-file. In this file the information of the load curve and the operating strategy are stored together. Below the content of an example file is shown:

Spain_2014_4Periods.gpa

```
Name:        Spain_2014_4Periods
Source:      DLR
Contact:     greenius Team
Res:         365x24
Weekday:         0
Scaling      500000.00

LoadData     PeriodData
0    4
0    4
0    4
0    4
0    4
0    2
...
0    2
0    1
0    2
0    4
0    4

Hint: -1 means TRUE
Anzahl Perioden: 9
DNI threshold for sunperiod: 0
StoDispThre DispFracWS  DispFracWOS StoBuffThre StoBuffLev  MinPBInput
MaxPBInput  FuelFrac    FillStorageToMin    UseFossilForStorageFillToMin
GasFillLastHour GasFillUp
0   1   1   0   0   0   1   0   -1  0   0   0
0   1   1   0   0.6 0   1   0   -1  0   0   0
0   1   1   0   0.4 0   1   0   -1  0   0   0
1   0   0   0   1   0   0   0   -1  0   0   0
0   0   0   0   0   0   0   0   -1  0   0   0
0   0   0   0   0   0   0   0   0   0   0   0
0   0   0   0   0   0   0   0   0   0   0   0
0   0   0   0   0   0   0   0   0   0   0   0
0   0   0   0   0   0   0   0   0   0   0   0
```

At the beginning some general information is given. The resolution (`Res:`) describes the number of time steps per year. The value `365x24` refers to an hourly resolution of the load curve and the operating strategy. Other temporal resolutions are possible as described in the simulation section. "Scaling" is the nominal value to which the fractions in the load curve refer to.

The first matrix with two columns contains the load curve and the period data. The number of lines conforms to the above mentioned resolution. The following four lines have only informal character. The number of different strategies cannot be different from 9. The following matrix stores the parameters of the operating strategy. Each line represents one strategy and holds the values in the order stated in the line above the matrix. **Note that `-1` in the last four columns means TRUE**.

Examples of operating strategies

The following examples of operating strategies were created for an Andasol-1-like plant with 7.5 hour full-load storage and a fossil fired auxiliary heater. The auxiliary heater is able to provide the heat needed for full load operation of the power block. For other plant configurations the operating strategies must eventually be adapted.

Solar Only

Solar Only is the reference strategy for a CSP plant. Whenever there is enough solar heat available the power block is operated. Solar heat which cannot be used by the power block is used to charge the storage. The excess solar heat is dumped. Only the loss compensation of the storage has a higher priority than serving the power block. This helps to prevent the storage content from freezing which would result in a damaged storage. When there is not enough solar heat to run the power block at full load, the heat to the power block is filled up with heat from the storage. This operating strategy ensures the utilization of the maximum amount of solar heat. The plant runs at part load for many hours, so the thermal efficiency of the power block is not optimal. An example of this strategy is available from the file called "Solar Only.gpa".

Optimized Gas

The operating strategy Optimized Gas increases the power block load to its maximum in every operating hour by using heat from the auxiliary fossil burner. The increased load results in a higher thermal yearly efficiency of the power block. For this operating strategy, the burner has to be able to deliver the difference in heat between minimum and maximum load of the power block. An example of this strategy can be found in the file "Opt Gas 6-20 w_ autofill.gpa".

Reduced Number of Turbine Starts

Every start and stop of the steam turbine increases the maintenance efforts. This operating strategy is used to reduce the number of turbine. A small fossil burner, which only has to provide the minimal heat required for power block operation, is used to fill up the gaps in solar heat. In times when the burner assists, the power block is only running at minimal load. See file "Min Turb Starts w autofill.gpa" for an example of this operating strategy.

Load curve

For shifting the generation of electric power to high demand times, a load curve can be used. An example of a load curve is shown in the following table. The according **greenius**-file is called "central hour.gpa". Each day of a month has the same load curve. The generation of the power is shifted to the central hours of the day. The duration of the electricity production per day depends on the expected amount of solar heat for this time of the year. If the solar field is not able to deliver the required heat to fulfil the load curve a fossil burner is used to fill up the heat.

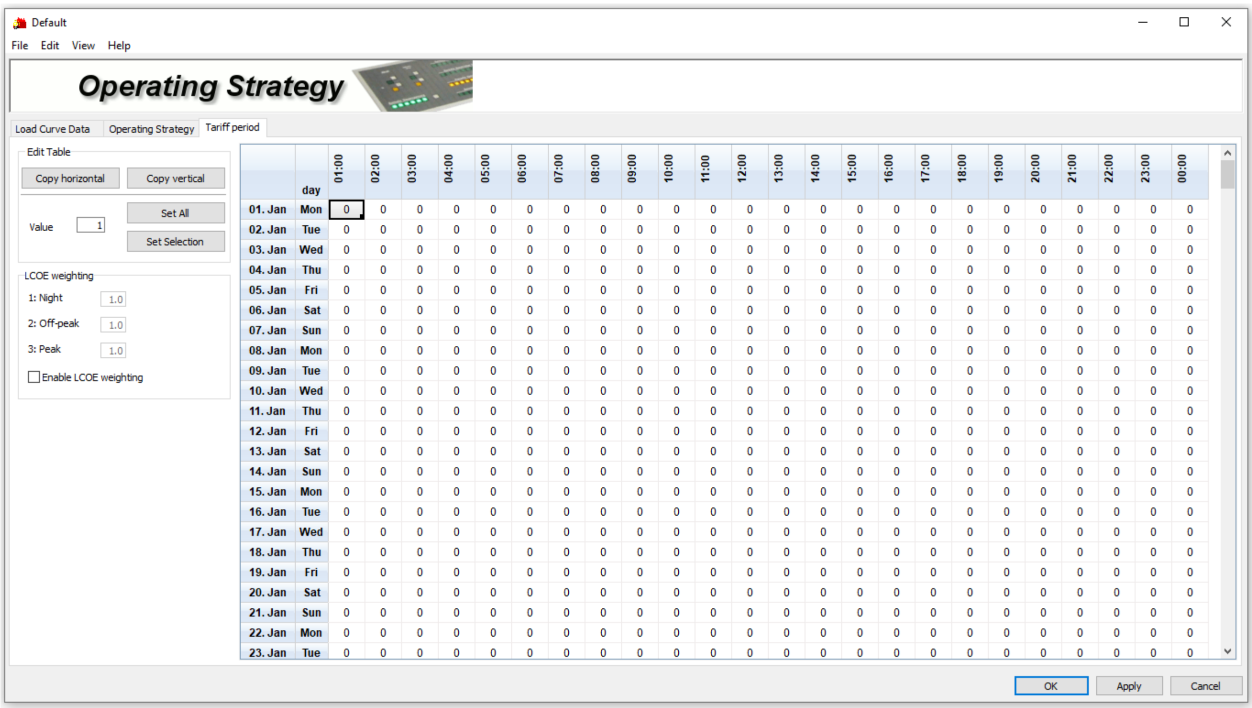
Month \ Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
January	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	4	4	2	2	2	2	1	1	1
February	1	1	1	1	1	1	1	1	1	1	1	2	2	2	3	4	4	3	2	2	2	1	1	1
March	1	1	1	1	1	1	1	1	1	1	1	2	3	4	4	4	4	4	4	3	2	1	1	1
April	1	1	1	1	1	1	1	1	1	1	3	4	4	4	4	4	4	4	4	4	4	3	1	1
May	1	1	1	1	1	1	1	1	1	3	4	4	4	4	4	4	4	4	4	4	4	4	3	1
June	3	1	1	1	1	1	1	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
July	3	1	1	1	1	1	1	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
August	1	1	1	1	1	1	1	1	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3
September	1	1	1	1	1	1	1	1	1	1	3	4	4	4	4	4	4	4	4	4	4	3	1	1
October	1	1	1	1	1	1	1	1	1	1	1	2	3	4	4	4	4	4	4	3	2	1	1	1
November	1	1	1	1	1	1	1	1	1	1	1	2	2	2	3	4	4	3	2	2	2	1	1	1
December	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	4	4	2	2	2	2	1	1	1

Period 1:	0% of eletric full-load
Period 2:	30% of eletric full-load
Period 3:	90% of eletric full-load
Period 4:	100% of eletric full-load

Tariff period

It is possible to weigh the LCOE for different day periods by filling the table below.

The table must be filled with 1 (night), 2 (off-peak) or 3 (peak). The electricity produced in every hour can be multiplied by the given factor for each period if the LCOE weighing is enabled.



Meteorology

Meteorological data is the basis for nearly all simulations that **greenius** can carry out. This software contains only a small number of meteorological data files. But powerful import filters can import meteo data from several other sources (the first 4 ones provide the required TMY datasets free of charge and Meteonorm is available for a reasonable price):

- *TMY2 data from NREL (*.tm2)*
  greenius comes with a TMY2 filter that can import the 239 free meteorological data sets of the USA. These data sets can be downloaded from the Internet at: http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/tmy2/. TMY2 data files can be

loaded directly in the load meteo file dialogue.

- *EnergyPlus Weather Data, PVGIS (*.epw)*
  The weather data can be downloaded from JRC Photovoltaic Geographical Information System (PVGIS) - European Commission
  The downloaded zip-File contains a `*.epw` file with the actual meteo data. It can be loaded directly via the load meteo file dialogue.

- Data from the NREL National Solar Resource Database (*.csv). This database contains not only US data but also TMY datasets for other regions throughout the world. See the detailed description in section Import Meteo Data from NSRDB.

- *DWD Test Reference Years (Deutscher Wetterdienst) (*.dat)*
  DWD provides TRY for Germany, which may be downloaded for free after registration from https://kunden.dwd.de/obt/
  It should be mentioned here, that these TRY files are not made for solar thermal applications, according the DWD TRY handbook. We have made a comparison for some sites and observed a considerable differences in GHI and particularly in DNI between DWD and Metonorm datasets. Therefore the utilization of these DWD TRYs in **greenius** may lead to results with high uncertainty.

- *Meteonorm Software*
  With the use of the *METEONORM software,* TMY data files for every site at the earth can be generated. A detailed description is given in the section Create Meteo Data with METEONORM.

If you want to use these import filters, you should use the Meteo -> Load button and chose the desired extension from the "File type" choice box.

Please be aware of the fact that the ability of **greenius** to read the various meteo data file formats should really be interpreted as *import function*. After importing the meteo data it should be stored in the proprietary `*.gpa` format which will also be saved together with the project. You can easily create a *.gpa file via *File->Save as...*
Furthermore, we want to emphasize that these complimentary TMY datasets may be sufficient for pre-feasibility studies, but for yield calculations in advanced project planning stages, datasets with lower uncertainties should be used.

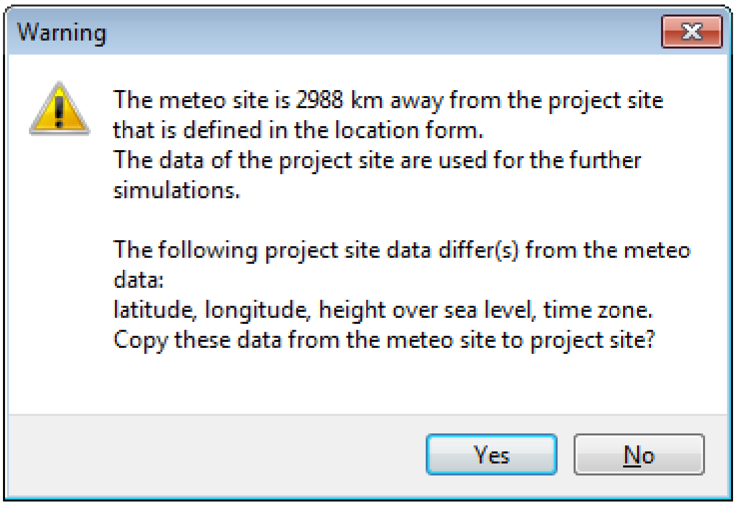
greenius itself uses the same file format for the meteorology component as for all other components with the file extension `*.gpa`. A complete **greenius** meteo data file contains for each time step of a reference year a data set with the following 8 values:

- Ambient temperature
- Air Pressure
- Relative humidity
- Global irradiance
- Direct normal irradiance
- Diffuse irradiance
- Wind direction
- Wind speed

The number of data sets varies with temporal resolution of the meteo file (365x24=8760 for hourly resolution, 365x48 for 30 minutes resolution, and so on). **greenius uses the temporal resolution of the meteo data file to determine the time steps for the simulation!** You may find more information on temporal resolution in the simulation section.

Most of the simulations can be also performed without complete meteo data sets, solely the major ambient condition for the respective technology must be provided. That means: for simulation concentrating solar power plants the direct normal irradiance is required, for wind power plants the wind speed and for PV plants the global irradiance.

Latitude, longitude and time zone represent the measurement point of the meteorological data. This should be as near as possible at the planned project site (see Location). When loading a meteorological data file **greenius** checks possible deviations and may produce a warning message (see below). If the project site is too far away from the meteo site, inconsistencies can occur in the calculations because the project site location is used for all sun position calculations. This can lead to the situation that the sun's position is determined to be below the horizon (before sunrise), but the meteo file states a positive irradiance value. Therefore it is usually recommended to hit *Yes* in the warning message window which results in copying the geographic data from the meteo data component to the Location component.



Meteo Data Processing and Presentation

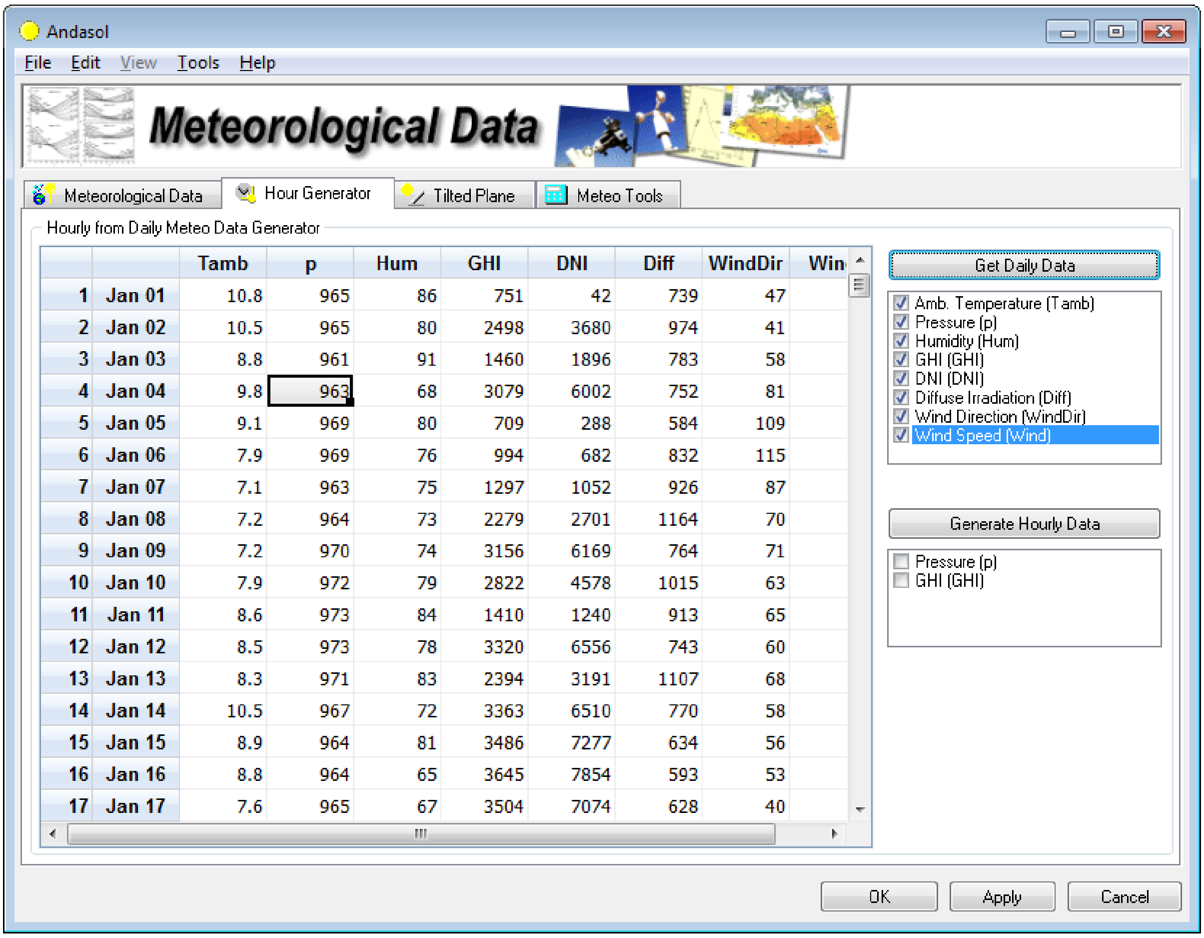
greenius offers the following presentation possibilities for meteorological data:

- Table of all hourly values
- Table of all mean monthly values
- Plot of the mean monthly values
- Plot of hourly values for chosen days and parameters
- Histogram of chosen parameters
- Isolines of mean monthly values
- Wind rose

All tables and graphics can also be copied via the clipboard to other applications.

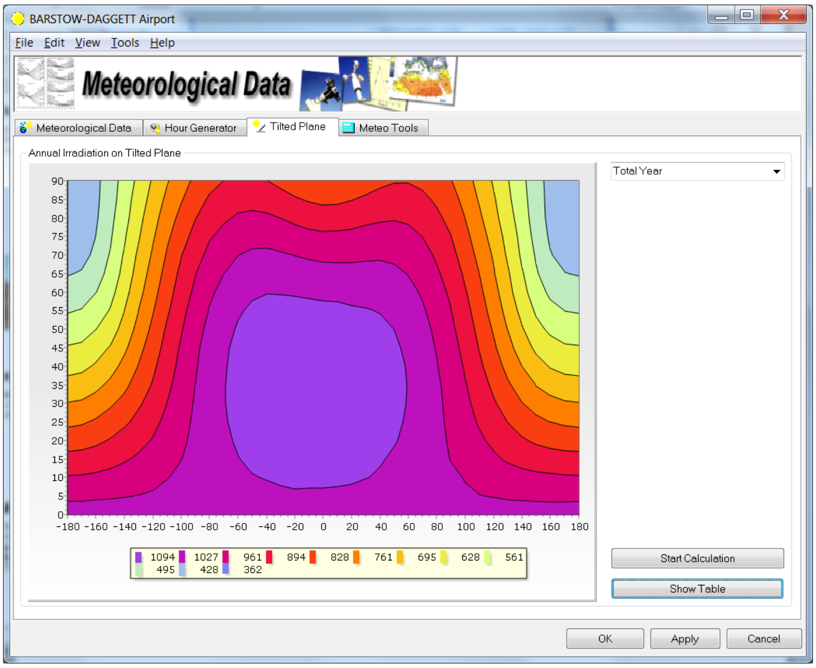
Hourly Generator

greenius has a simple hour value generator that can generate hourly global irradiance and pressure values using daily values. Just paste the daily values from the clipboard and click on ↳*Generate Hourly Data*. The calculated hourly values are then written into the table in the tab *Meteorological Data*. It is also possible do go the other way around and calculate mean daily values and daily sums from the hourly values by clicking ↳*Get Daily Data*.



Tilted Plane

This tool is useful to get an idea of the magnitude of losses induced by the non-optimal orientation of non-tracking solar collectors, e.g. PV panels. Based on the given coordinates and GHI in the *Meteorological Data* tab, **greenius** calculates the sun azimuth and sun elevation and total irradiance (diffuse + direct) on a tilted plane. This calculation is done for all possible module azimuth angles in steps of ten degrees and all possible elevation angles in steps of five degrees. The result is visualized in the corresponding graph.



Meteo Tools

In the tab Meteo Tools you have the possibility to calculate extraterrestrial irradiance and check if your irradiance data for a certain time step is realistic. There are two different views of this tab between which you can switch with the button *Show Table* respectively *Show Values.*

The upper group box *General Input* is visible in both views and provides information about the site for which the value are calculated. You can also define date and time for the calculation. **greenius** calculates the position of the sun at the given time and date as well as the times of sunrise, solar noon and sunset. All the values are displayed in the two group boxes *Position of the Sun* and *Sunset and Sunrise*.

The group box Irradiance Comparison states a variety of irradiance measurements. The global horizontal irradiance (GHI) is always equal to the sum of direct horizontal (DHI) and diffuse horizontal irradiance (DiffHI). The direct normal irradiance (DNI) can be calculated from the DHI and vice versa using the following equation:

$$DHI = cos(90 - \gamma_s) \cdot DNI$$

The right column gives the extraterrestrial values of these four irradiance components. Extraterrestrial means in this context that the influence of the atmosphere on the solar radiation is neglected. This allows to calculate the direct normal irradiance only based on the given date and time. The extraterrestrial diffuse irradiation is always zero because no scattering at atmospheric molecules and particles can occur. Consequently, the direct and global horizontal irradiance can be determined easily.

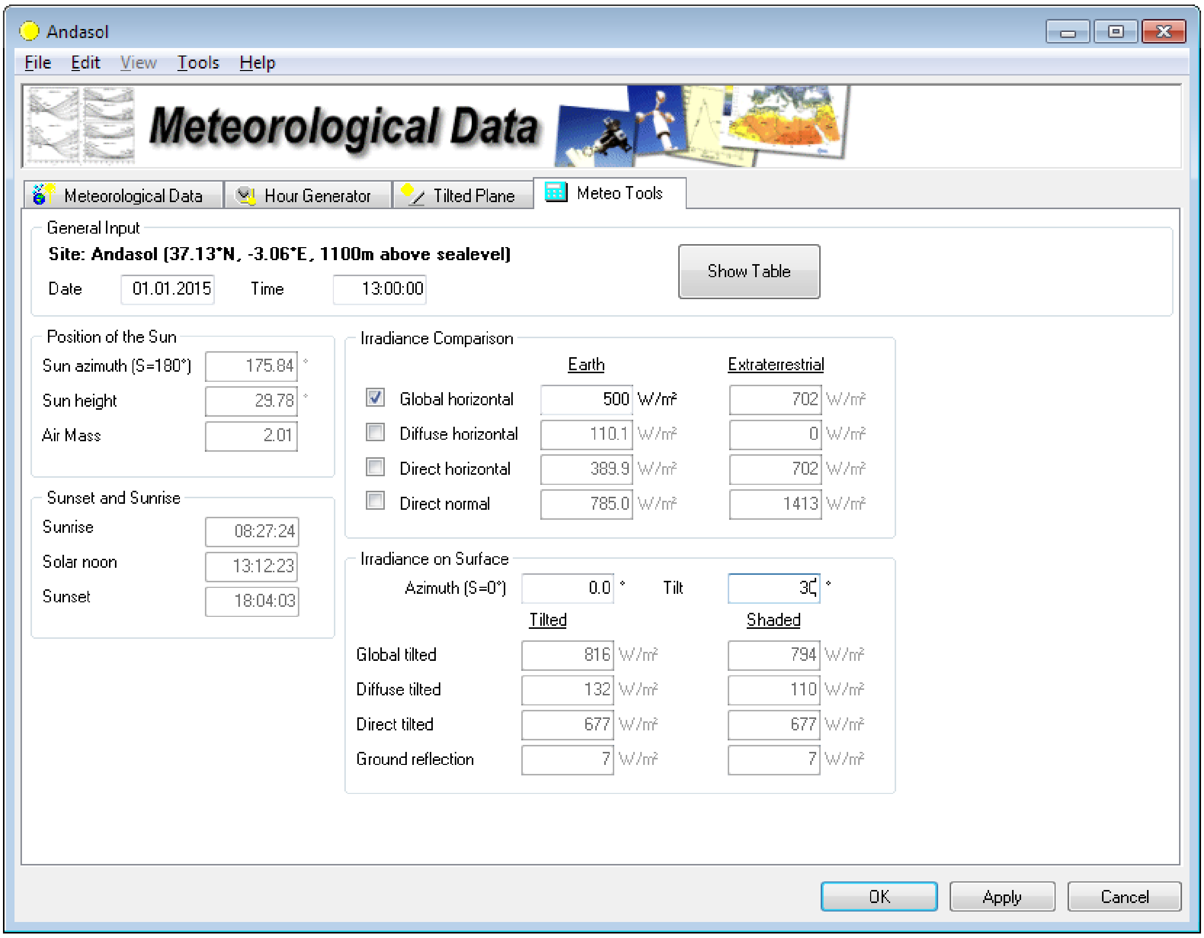
The values in the first column represent measurements on the earth's surface where the global irradiance is reduced due to absorption and reflection and the diffuse component of the light can be significantly high. The four values can be changed as soon as the corresponding check box is checked. **greenius** calculates automatically the other irradiance values as soon as the input data is sufficient. Possible input combinations are:

- GHI (in this case **greenius** assumes a ratio of diffuse light)
- GHI + DiffHI
- GHI + DHI

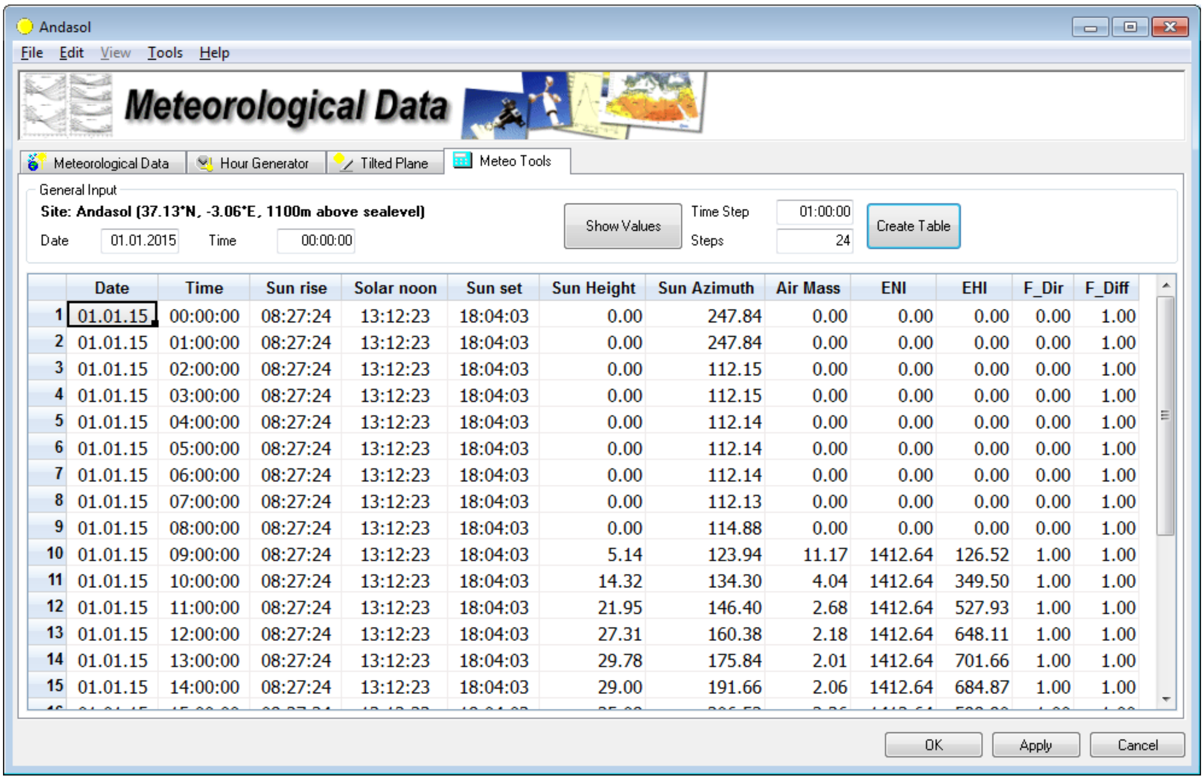
- GHI + DNI
- DiffHI + DHI
- DiffHI + DNI

Whenever the input irradiance values are modified **greenius** calculates the missing earth irradiance values. Unrealistic values will be coloured red. **Note that the earth irradiance values can never be higher than the corresponding extraterrestrial values!**

The group box Irradiance on Surface allows the calculation of the irradiance on an arbitrarily oriented plane. The orientation is set with the azimuth and the tilt value. **Note that for the plane azimuth 0° means south while for the sun azimuth output 0° means north!** For the first column the irradiance values are calculated disregarding the shading defined in the shading editor, in the second column shading is included.



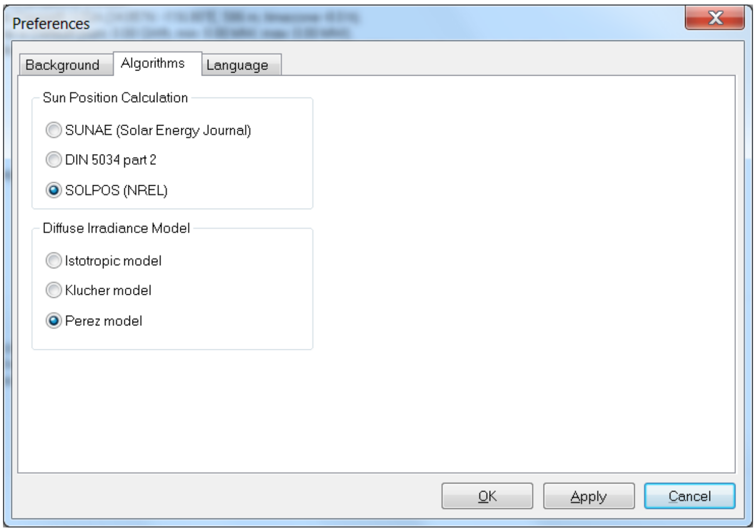
When you switch to the second view using *Show Table* where you can define a step length and a number of steps for the creation of a table with some values related to the solar position, extraterrestrial irradiance and shading factors for direct and diffuse irradiation. The calculations are started with *Create Table*.



	Date	Time	Sun rise	Solar noon	Sun set	Sun Height	Sun Azimuth	Air Mass	ENI	EHI	F_Dir	F_Diff
1	01.01.15	00:00:00	08:27:24	13:12:23	18:04:03	0.00	247.84	0.00	0.00	0.00	0.00	1.00
2	01.01.15	01:00:00	08:27:24	13:12:23	18:04:03	0.00	247.84	0.00	0.00	0.00	0.00	1.00
3	01.01.15	02:00:00	08:27:24	13:12:23	18:04:03	0.00	112.15	0.00	0.00	0.00	0.00	1.00
4	01.01.15	03:00:00	08:27:24	13:12:23	18:04:03	0.00	112.15	0.00	0.00	0.00	0.00	1.00
5	01.01.15	04:00:00	08:27:24	13:12:23	18:04:03	0.00	112.14	0.00	0.00	0.00	0.00	1.00
6	01.01.15	05:00:00	08:27:24	13:12:23	18:04:03	0.00	112.14	0.00	0.00	0.00	0.00	1.00
7	01.01.15	06:00:00	08:27:24	13:12:23	18:04:03	0.00	112.14	0.00	0.00	0.00	0.00	1.00
8	01.01.15	07:00:00	08:27:24	13:12:23	18:04:03	0.00	112.13	0.00	0.00	0.00	0.00	1.00
9	01.01.15	08:00:00	08:27:24	13:12:23	18:04:03	0.00	114.88	0.00	0.00	0.00	0.00	1.00
10	01.01.15	09:00:00	08:27:24	13:12:23	18:04:03	5.14	123.94	11.17	1412.64	126.52	1.00	1.00
11	01.01.15	10:00:00	08:27:24	13:12:23	18:04:03	14.32	134.30	4.04	1412.64	349.50	1.00	1.00
12	01.01.15	11:00:00	08:27:24	13:12:23	18:04:03	21.95	146.40	2.68	1412.64	527.93	1.00	1.00
13	01.01.15	12:00:00	08:27:24	13:12:23	18:04:03	27.31	160.38	2.18	1412.64	648.11	1.00	1.00
14	01.01.15	13:00:00	08:27:24	13:12:23	18:04:03	29.78	175.84	2.01	1412.64	701.66	1.00	1.00
15	01.01.15	14:00:00	08:27:24	13:12:23	18:04:03	29.00	191.66	2.06	1412.64	684.87	1.00	1.00

Sun position and irradiance data

greenius comes with different sun position algorithms and the user may choose one of them via the *File|Preferences|Algorithm* menu entry.



Since the meteorological data files give mean values for the respective hour, the case may occur that the meteorological file contains significant DNI values while the sun position algorithm calculates a sun position below the horizon for early morning or late afternoon hours. That means the sunrise is in the second half or sunset is in the first half of that individual hour. In these cases **greenius** does not use the sun position for the centre but rather for the edge of that hour.

Technology

greenius offers a variety of technologies that can be calculated. They can be chosen via the technology selection form. At the moment, the supported technologies are:

- Solar thermal power plants with or without thermal storage using parabolic trough or Fresnel collectors
- Process heat generation with parabolic troughs, Fresnel or non-concentrating collectors
- Absorption chillers with parabolic troughs, Fresnel or non-concentrating collectors
- Power tower systems
- Solar thermal Dish Stirling systems
- Grid-Connected photovoltaic systems
- Concentrating photovoltaic systems
- Wind power parks
- Fuel cell systems

Select Technology

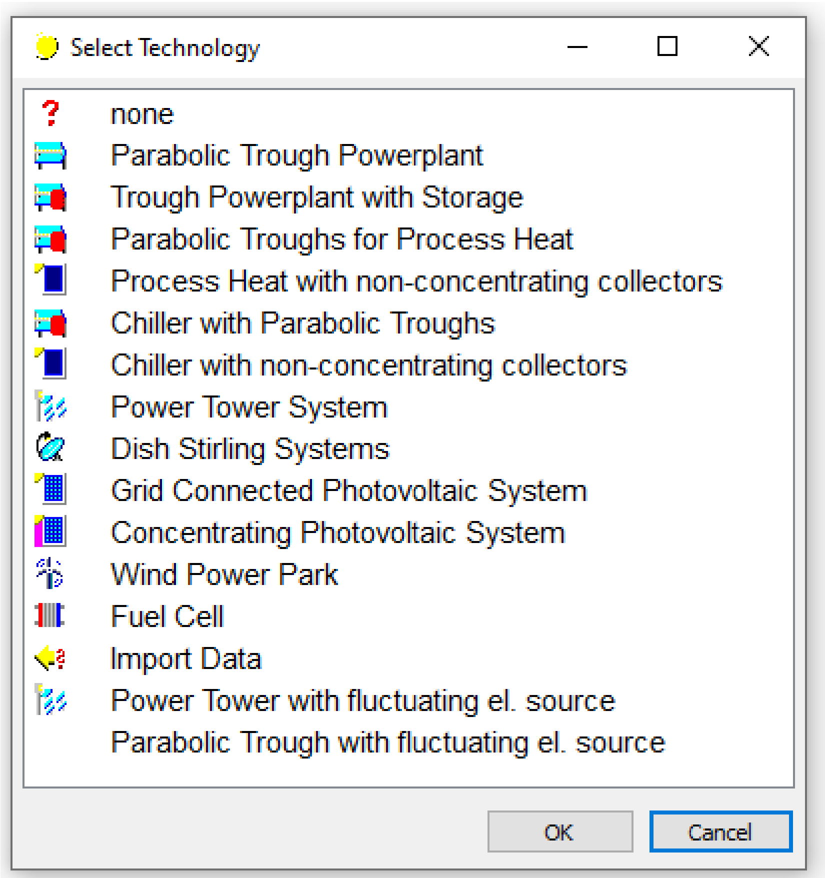
You can start the technology select window with *Ctrl-T*, with a right mouse click on the main screen or at the menu entry *Project Case|Select Technology*.

In this window you can select the technology. At the moment **greenius** supports the following technologies:

- Parabolic Trough Power Plants
- Parabolic Trough Power Plants with Storage
- Parabolic Troughs for Process Heat
- Process Heat according to ISO 24194
- Chiller with Parabolic Troughs
- Chiller with Non-Concentrating Collectors
- Dish Stirling Systems
- Grid Connected PV Systems
- Concentrating PV Systems
- Wind Power Park
- Fuel Cell
- Fuel Cell with Storage
- Data Import
- Power Tower with fluctuating el. source
- Parabolic Trough with fluctuating el. source

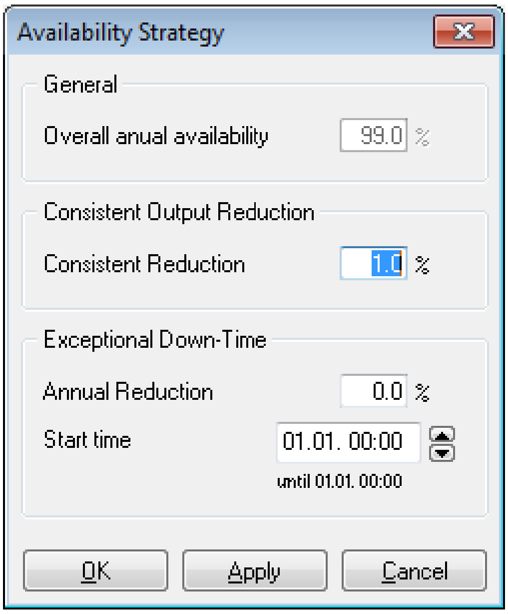
The data import option offers the possibility to import results of technical simulations from other programs in order to use the economical calculations of **greenius**.

Not saving after changing the parameters can result in the loss of data. *Esc* or *Cancel* close the technology selection window without changing the technology. *Enter* respectively *OK* confirms the selection. **This replaces all technology parameters in the current project**.



Availability

The availability form appears in several technologies. Two different approaches can be combined: First, a constant factor can be used to reduce the availability of the system. This factor is applied for the whole year. Additionally, a dedicated maintenance period can be defined during which the whole solar field is shut down. The default value is 99% constant reduction without maintenance.



Parabolic Trough Power Plants

This technology is the most important technology in **greenius** and it is the one with the most detailed models. It consists of several subsystems, which are described in the following chapters. Apart from the thermal storage component there is no difference between the storage and the non-storage alternative in the technology selection form.

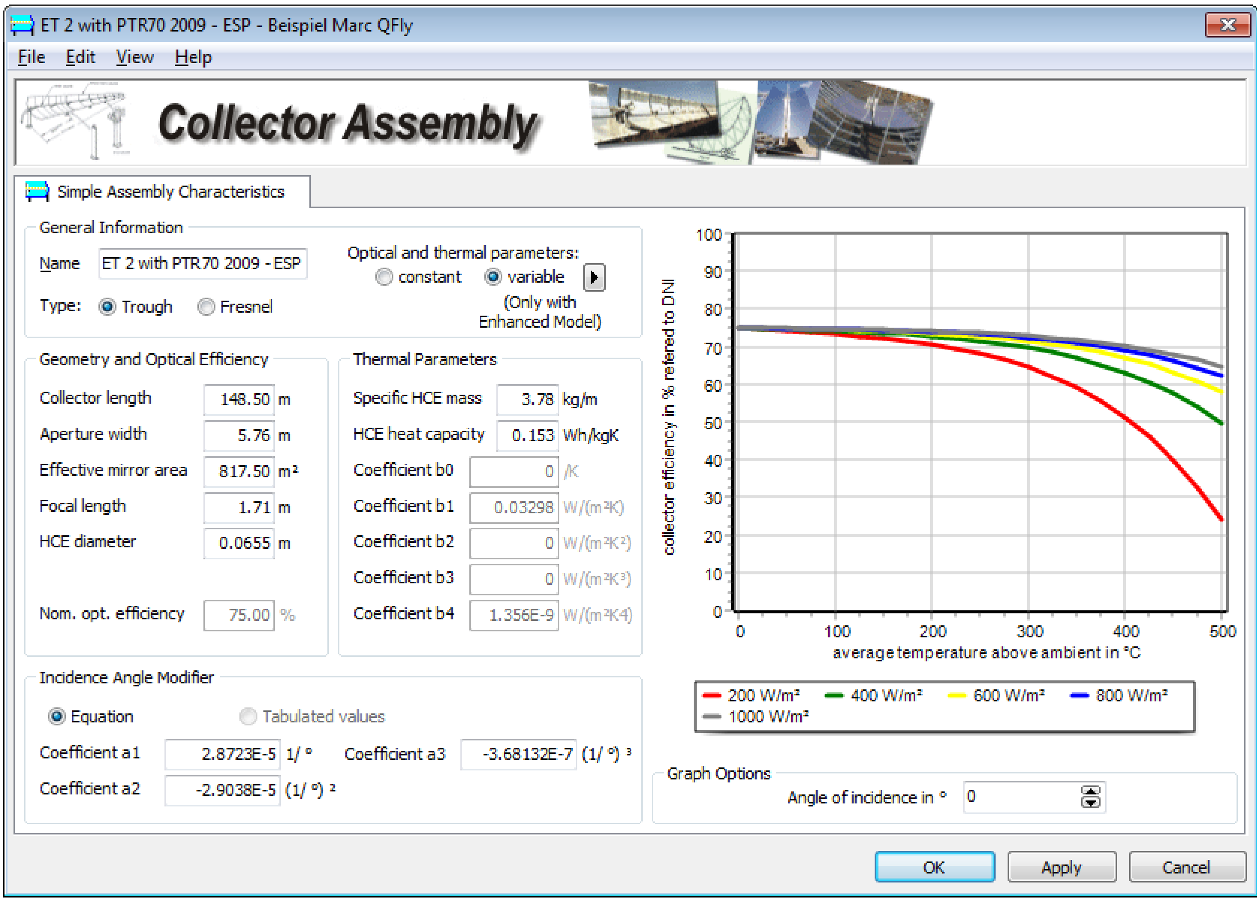
The following components exist for parabolic trough power plants:

- Trough collector
- Trough field
- Thermal storage (in case of the alternative with thermal storage)
- Boiler
- Power block

Collector Assembly

The component *Collector Assembly* is used to model a parabolic trough (PT) or linear Fresnel (LF) collector. The collector form where you can define the relevant parameters for both collector types is shown below. Some formulas below are different for PT and LF collectors. The following general description aims at PT collectors, while the deviating definitions for LF collectors are discussed in a separate subsection at the end.

Within the *General Information* box you can also define whether to use constant or variable parameters for optical efficiency and absorber heat losses. Constant parameters are sufficient for most applications. More detailed analyses are possible using temporal and locally dependent parameters. Be aware that variable parameters can only be used together with the spatially resolved enhanced field model, not with the simple model. The definition of variable parameters is described in a separate section below.



The collector efficiency is calculated based on the empirical formula below

$$\eta_{collector} = K \cdot \eta_{opt,0} \cdot \eta_{cleanliness} - \left(K \cdot b_0 \cdot \Delta T + \frac{b_1 \cdot \Delta T + b_2 \cdot \Delta T^2 + b_3 \cdot \Delta T^3 + b_4 \cdot \Delta T^4}{DNI} \right)$$

The parameters b_i defining the heat losses of the receiver tubes are estimated from experimental data, from manufacturer's data sheets or from literature. While $\eta_{opt,0}$ is the the optical collector efficiency at incidence angle $\theta = 0$, the factor K expresses the dependency of the optical efficiency η_{opt} on the incidence angle of the solar radiation and thus the position of the sun. At two-axis tracked systems K is equal to 1 because $\theta = 0$ is always valid. For parabolic trough collectors K is defined by

$$K = IAM \cdot \cos\theta$$

where *IAM* denotes the Incidence Angle Modifier which is determined using an empirical formula

$$IAM = 1 - \frac{a_1 \cdot \theta + a_2 \cdot \theta^2 + a_3 \cdot \theta^3}{\cos\theta}$$

with the parameters a_i that must be provided by the user. Be aware of the above definition of the IAM in order to provide the correct parameters.

The temperature difference in this equation is defined as the difference between ambient temperature and arithmetic mean temperature between collector inlet and outlet:

$$\Delta T = \frac{T_{SF,in} + T_{SF,out}}{2} - T_{amb}$$

The other component parameters define the collector dimensions and thermal behaviour that is used for the calculation of effects caused by thermal inertia of the solar field.

The graph window at the right hand side can be used to display the collector efficiency and the IAM. Switch between both using the menu entry *View.* When displaying the IAM you can choose whether to include (which is equal to K in the formulas above) or exclude the cosine losses.

Divergent Definitions for Fresnel Collectors

This same input form is used to simulate linear Fresnel collectors, which are considered as "special case" of troughs in **greenius**.

For linear Fresnel collectors the IAM depends on two incidence angles: the longitudinal angle θ (corresponding to the incidence angle for parabolic troughs) and the transversal angle ϕ. In contrast to parabolic trough collectors the IAM dependency must be given by a table (if not visible use *View|IAM Table*). This method has been chosen because a simple function with one or two parameters is not suitable to fit the complicated IAM dependency of this collector type. The tabulated K-values for linear Fresnel collectors *include the cosine losses and end losses*. Therefore, **greenius** will **not** account for any end loss gain even if the corresponding box is checked.

Triples of angle, K_{long} and K_{trans} can be modified in the table. The parameter K for the equations above is the product of longitudinal and transversal value:

$$K = K_{long} \cdot K_{trans}$$

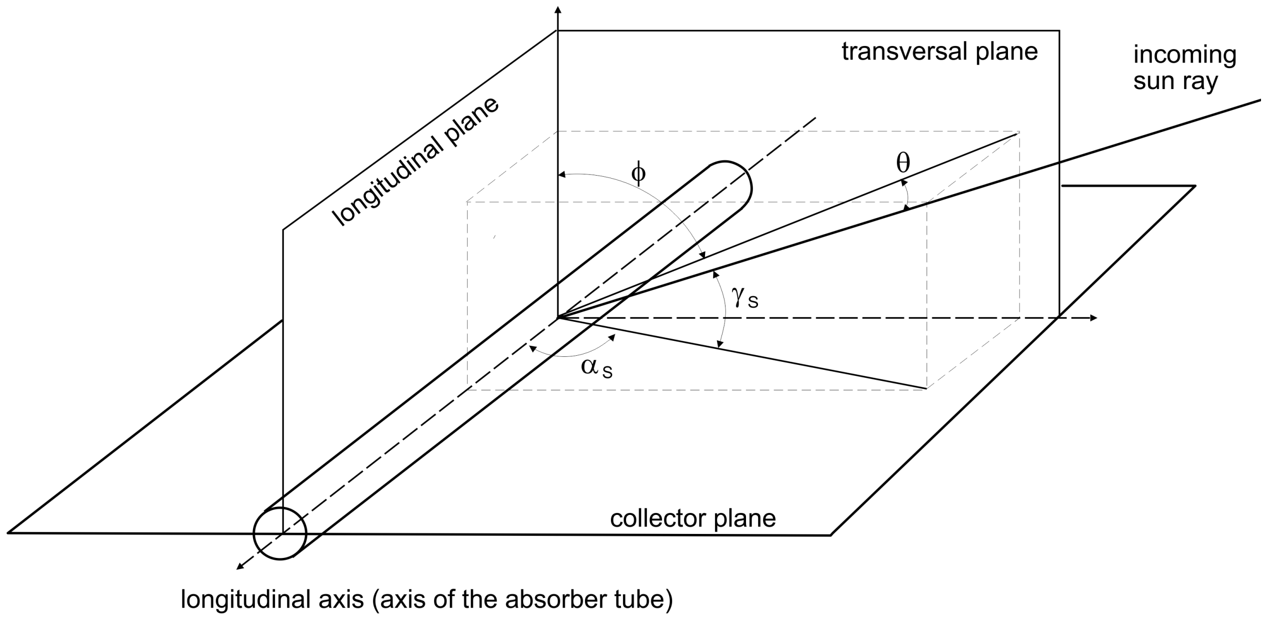
It is not necessary to calculate K values excluding the cosine losses and afterwards multiplying with the cosine loss factor for the irradiation on a horizontal collector plane like as shown below:

$$K = \frac{K_{long}}{\cos\theta} \cdot \frac{K_{trans}}{\cos\phi} \cdot \cos(90° - \gamma_s)$$

This transformation is useless since the following trigonometric relation is valid (also see [Mer09]):

$$\cos(90° - \gamma_s) = \cos\theta \cdot \cos\phi$$

The following graph explains the definition of the incidence angles for linear Fresnel collectors.



γ : angle between sun and collector plane

θ : longitudinal incidence angle

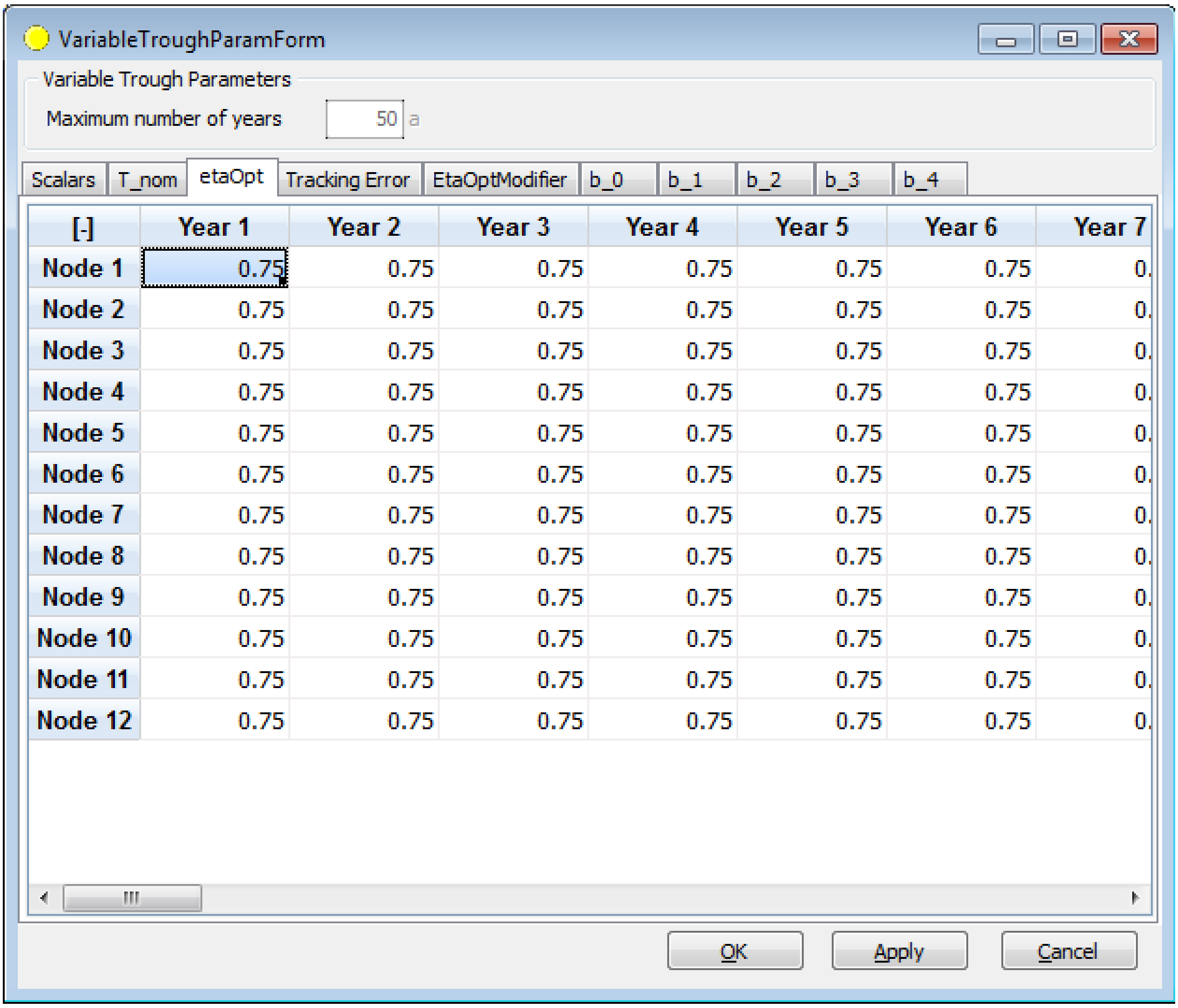
ϕ : transversal incidence angle

Usage of Variable Parameters for Optical Efficiency and Absorber Heat Losses

The *variable trough parameter form* is opened by clicking the small black triangle next to the radio button for *variable* parameters in the *collector assembly form*. All parameters set in the tabs of the this form have an impact on the *optical efficiency* of the collector or the *absorber heat losses*. Please note that **greenius** does not simulate the whole solar field but only one single representative loop. Therefore the properties defined for each node should be a mean value averaged over all loops of the solar field.

The tabs *etaOpt* and *b_0* to *b_4* have an identical functionality. They replace the constant definition of an optical efficiency respectively heat loss coefficients by a variable definition depending on the position in the loop (node) and the year of operation. Those additional degrees of freedom allow a more detailed model of the solar field. For example, it is possible to account for degradation of optical components or increasing heat losses due to hydrogen diffusion into the vacuum over the life time of the solar field.

The maximum number of years for parameter definition is set to 50. Values exceeding the life time of the plant defined in the Timing Form are neglected.



[-]	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Node 1	0.75	0.75	0.75	0.75	0.75	0.75	0.
Node 2	0.75	0.75	0.75	0.75	0.75	0.75	0.
Node 3	0.75	0.75	0.75	0.75	0.75	0.75	0.
Node 4	0.75	0.75	0.75	0.75	0.75	0.75	0.
Node 5	0.75	0.75	0.75	0.75	0.75	0.75	0.
Node 6	0.75	0.75	0.75	0.75	0.75	0.75	0.
Node 7	0.75	0.75	0.75	0.75	0.75	0.75	0.
Node 8	0.75	0.75	0.75	0.75	0.75	0.75	0.
Node 9	0.75	0.75	0.75	0.75	0.75	0.75	0.
Node 10	0.75	0.75	0.75	0.75	0.75	0.75	0.
Node 11	0.75	0.75	0.75	0.75	0.75	0.75	0.
Node 12	0.75	0.75	0.75	0.75	0.75	0.75	0.

With constant parameters **greenius** takes only several seconds for an annual simulation. Using variable parameters can increase computational time significantly because each year of operation is simulated separately. The results in Typical Operation Year (TOY) will be displayed only for the first year of operation, while the key results are shown for each year of operation.

The *etaOptModifier* can be used to manipulate the optical efficiency during the year. This may be useful for e.g. modelling different cleaning strategies. The etaOptModifier must be defined for each time step, therefore the temporal resolution must match to the temporal resolution of the meteo data file used.

Additionally, two more effects - temperature dependency of the optical efficiency and tracking errors - can be modelled. Therefore two additional parameters *etaOptTemp* and *etaOptTrack* are introduced into the performance equation already shown above:

$$\eta_{collector} = K \cdot \eta_{opt,0} \cdot \eta_{cleanliness} \cdot \eta_{opt,temp} \cdot \eta_{opt,track} - \left(K \cdot b_0 \cdot \Delta T + \frac{b_1 \cdot \Delta T + b_2 \cdot \Delta T^2 + b_3 \cdot \Delta T^3 + b_4 \cdot \Delta T^4}{DNI} \right)$$

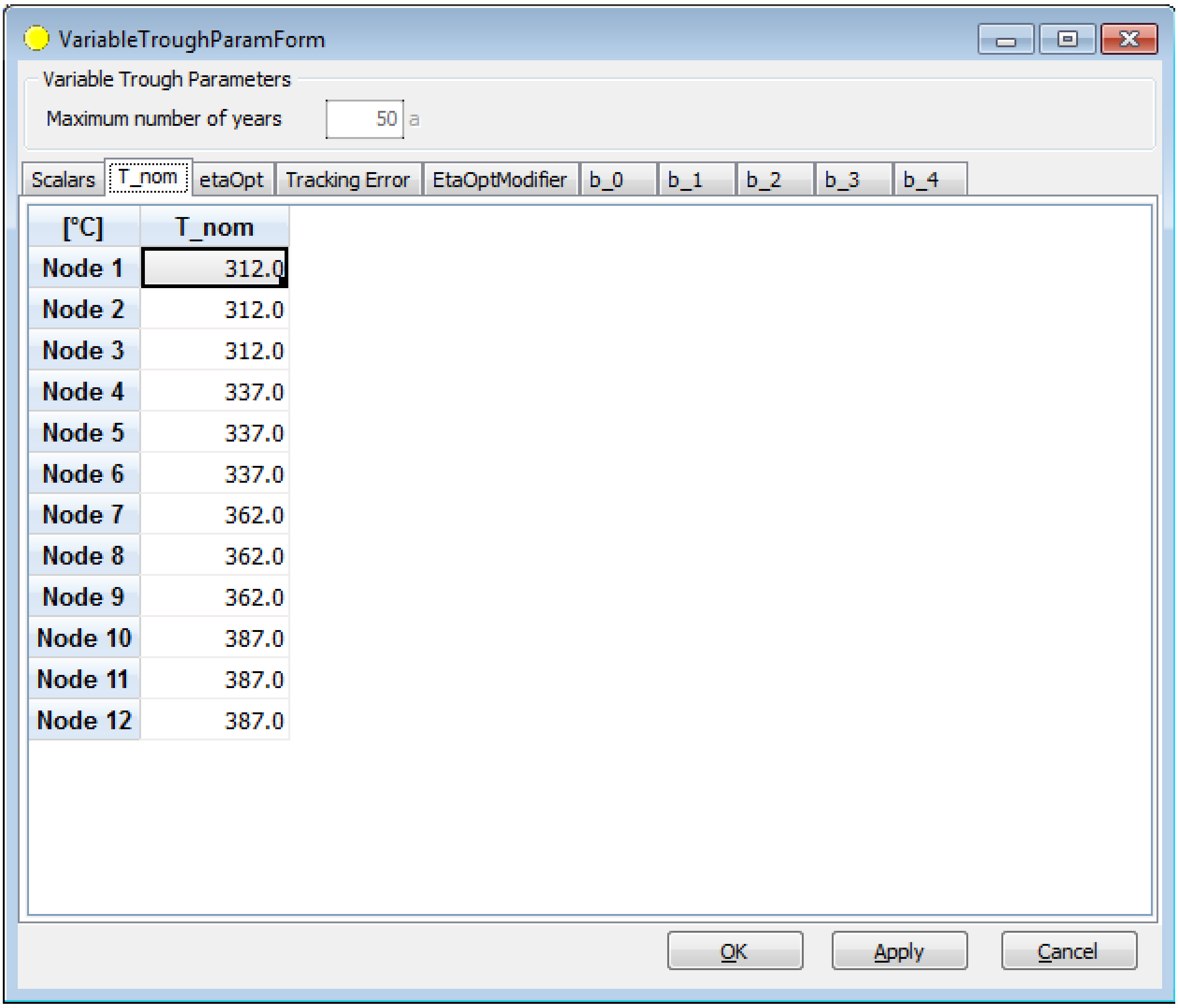
The temperature correction factor *etaOptTemp* is defined as a polynomial

$$\eta_{opt,temp} = 1 + temp_1 \cdot dT + temp_2 \cdot dT^2 + temp_3 \cdot dT^3$$

with

$$dT = |T_{mean,coll} - T_{mean,coll,nom}|$$

The coefficients *temp1*, *temp2* and *temp3* of the polynomial are defined in the tab *Scalars*. The temperature difference dT is the absolute value of the difference between nominal and actual collector temperature. **Please note, that it is not node, but collector temperature.** This is important, because the temperature dependency accounts for losses caused by the thermal expansion and lowering of the absorber tube when operating at temperatures below (or above) nominal point. This effect can only modelled for a whole collector (solar collector assembly, SCA) because a temperature deviation at one node has impact on other nodes in the same collector. Therefore, the mean temperature of all nodes is used for determination of dT. In the same time the nominal mean collector temperature must be defined by the user for each node. Thus the nominal values should be the same for all nodes of a single collector. The screen shot below shows typical nominal values for a solar field modelled by 12 nodes with four collectors per loop, inlet temperature of 300°C and outlet temperature of 400°C:



The factor etaOptTrack accounts for tracking errors of the solar field and is calculated as

$$\eta_{opt,track} = 1 + track_1 \cdot dTrack + track_2 \cdot dTrack^2 + track_3 \cdot dTrack^3$$

with

$$dTrack = |trackError| - trackNom$$

The coefficients *track1*, *track2* and *track3* of the polynomial are defined in the tab *Scalars*. *dTrack* is defined as the absolute value of the user defined tracking error subtracted by the nominal respectively tolerated tracking error *trackNom*. The actual tracking error *trackError* is defined by the user in tab *Tracking Error* by node and year of operation. The tolerated tracking error *trackNom* is defined in tab *Scalars*.

Collector Field

This component defines the dimensions of the collector field and piping, as well as heat transfer fluid type and operation parameters of the field. The form comes with 2 tabs called *Field Data* and *Field operation*. The menu entry *Costs* opens the field costs input window (see Costs).

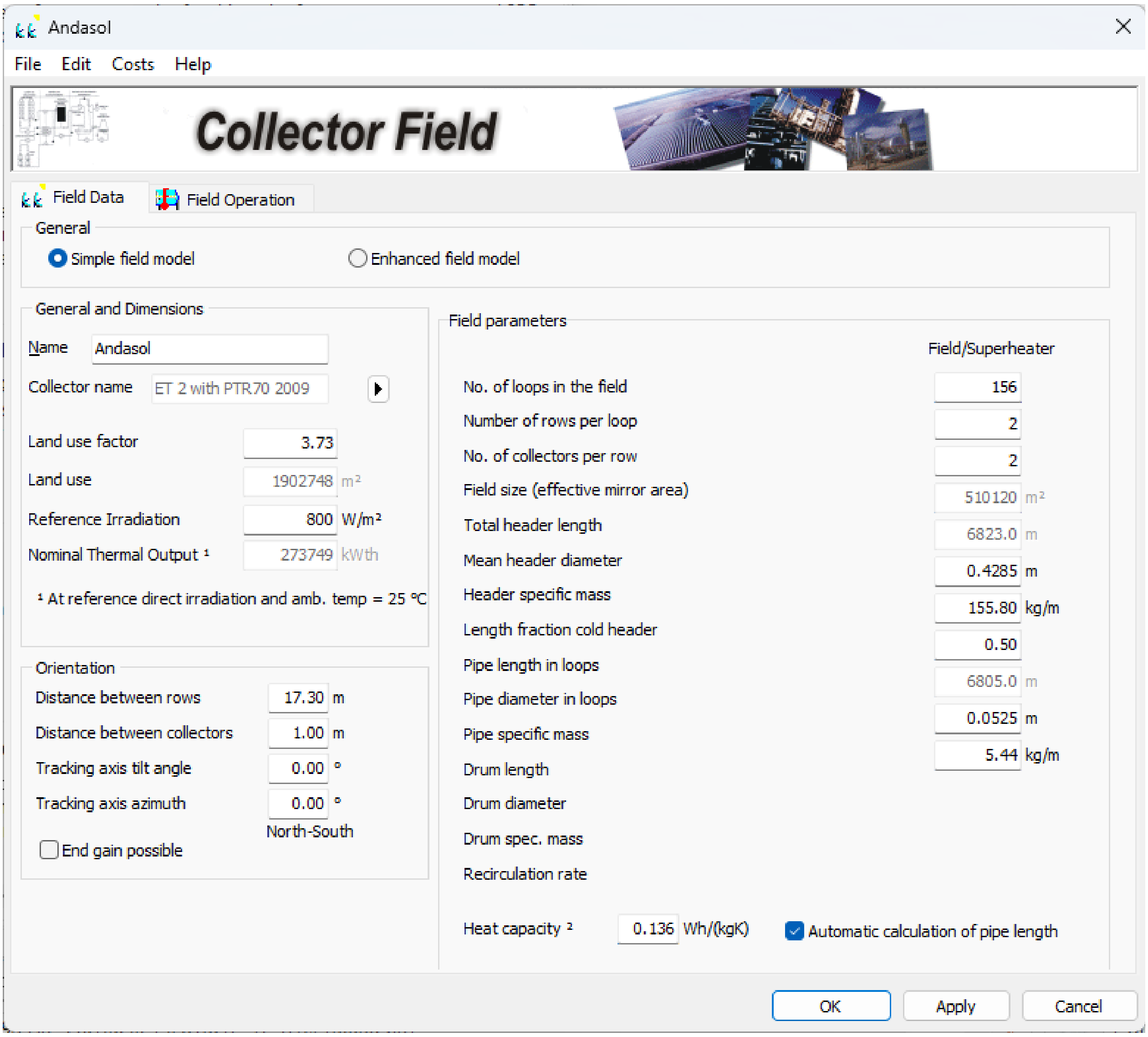
Tab Field Data

The user may choose between two different solar field models: a simple field model which uses the mean fluid temperature of a collector loop for the performance calculation and an enhanced field model where a collector loop is divided into *n* nodes. The energy balance is solved for each node individually leading to a more detailed temperature profile over the loop. The enhanced model is slightly slower than the simple model and was originally designed for the simulation of direct steam generation systems. Therefore it may only be used together with the fluid *Water IAPWS* (which can be chosen on the *Field Operation* tab). The adaptation of the enhanced model for single phase fluids is currently in progress. For more information on the models please refer to the subsection Available Field Models.

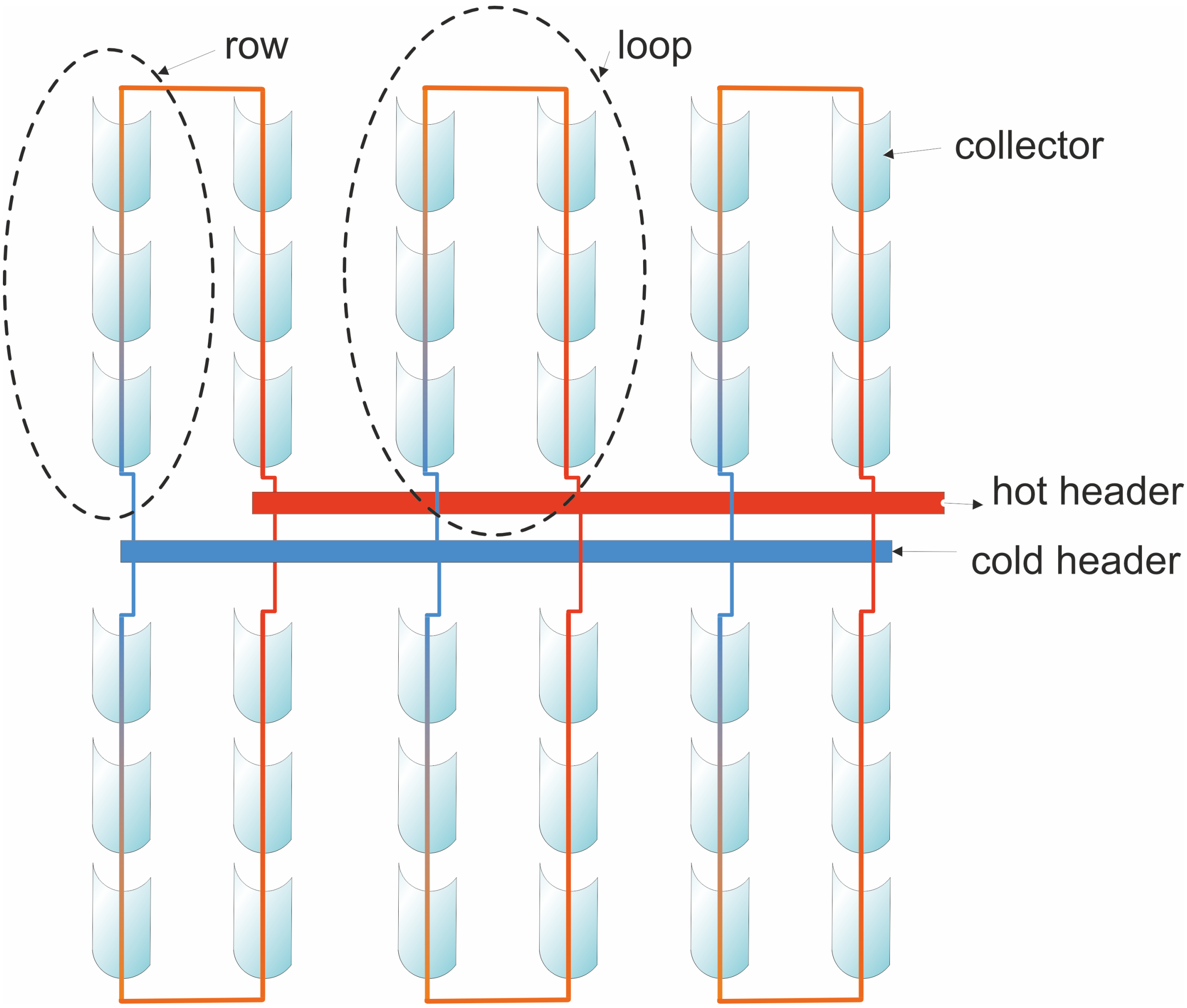
Field size and nominal thermal output are calculated continuously from the input values. This allows a step-by-step change of the parameters and dimensioning of the field. The nominal thermal field output shown here is calculated on the basis of the given values for solar field size, reference irradiation and the collector performance defined by the component *collector assembly*. Perpendicular irradiation, nominal collector temperatures as given on the *Field Operation* tab and ambient temperature of 25°C are assumed for this calculation.

The orientation of collector rows can be chosen: 0 means south-north, 90 means east west. This orientation is also shown below the input window using the verbal directions.

The tracking axis could be tilt towards the horizontal direction. The sign of this angle means: positive: tilted towards the sun, negative: tilted away from the sun.



The input values for *Number of loops in the field, No of rows per loop,* and *No of collectors per row* define the solar field size. The following figure shows the meaning of these parameters. *Loop* means a group of collectors connected in series between the cold and hot header. One *loop* can be made of several *rows* and one *row* contains several *collectors*.



It is important that pipe lengths and the mass of the heat transfer fluid are suitable for the field. If they are not correct, the results may be wrong, because these values define the thermal inertia of the field. If the volume of loop piping and headers are too large, a huge amount of solar energy is used to heat up the field and cannot be used for generating electricity. **greenius** distinguishes between the header on the one hand and the piping between the collector assemblies themselves and to the header on the other hand. For the total length of the header, the sum of the hot and cold header lengths must be entered. For the pipe length in loops, the sum of lengths in all loops must be entered.

Reasonable lengths of connecting pipes and headers are estimated automatically assuming a default H layout of the solar field. This automatic calculation may be disabled by just erasing the hook at ✎*Automatic calculation of pipe length* and/or ✎*Automatic calculation of fluid mass* (tab *Field Operation*) if your solar field layout differs considerably from the default H-shaped field layout. Especially for small process heat applications the manual calculation of pipe and header lengths is recommended.

The inner diameter of headers and pipes must be given by the user. A first estimation can be made by assuming that the header has the same free cross section as the sum of connected absorber tubes. This value may be multiplied by 0.66 to account for the reduction of headers with increasing distance from their solar field entrance. The following table shows typical values for diameter and specific mass of seamless steel pipes.

Nominal Pipe Size	Nominal Diameter	Outer Diameter	Wall Thickness	Inner Diameter	Specific Weight
inch	mm	mm	mm	mm	kg/m
1	25	33.4	3.38	26.64	2.50
1 1/2	40	48.3	3.68	40.94	4.05
2	50	60.3	3.91	52.48	5.44
2 1/2	65	73.0	5.16	62.68	8.63
3	80	88.9	5.49	77.92	11.29
4	100	114.3	6.02	102.26	16.08
5	125	141.3	6.55	128.20	21.77
6	150	168.3	7.11	154.08	28.26
8	200	219.1	8.18	202.74	42.55
10	250	273.0	9.27	254.46	60.29
12	300	323.8	10.31	303.18	79.71
14	350	355.6	11.13	333.34	94.55
16	400	406.4	12.7	381.00	123.31
18	450	457.0	14.27	428.46	155.81
20	500	508.0	15.09	477.82	183.43
24	600	610.0	17.48	575.04	255.43

Depending on the chosen field model (see below) the *length fraction cold header* must be set. Except for small process heat systems this value is usually 0.5.

The *heat capacity* of the pipes and headers can be modified if required. The default value is 0.121 Wh/(kg·K).

The input parameter *Reference Irradiation* is used to calculate the nominal thermal output of the solar field and is therefore a design value. In contrast to photovoltaic modules, there is no standard defining a reference irradiation for parabolic troughs. Experience has shown that a reference irradiation of 750 W/m² will result in a reasonable solar field size if the user designs the nominal solar field thermal output according to the nominal power block thermal input. This is of course only valid for a parabolic trough plant without thermal storage since the storage typically needs an oversized solar field. The solar field size found with the reference irradiation of 750 W/m² could then be used as starting point to find the solar field size with minimal LEC.

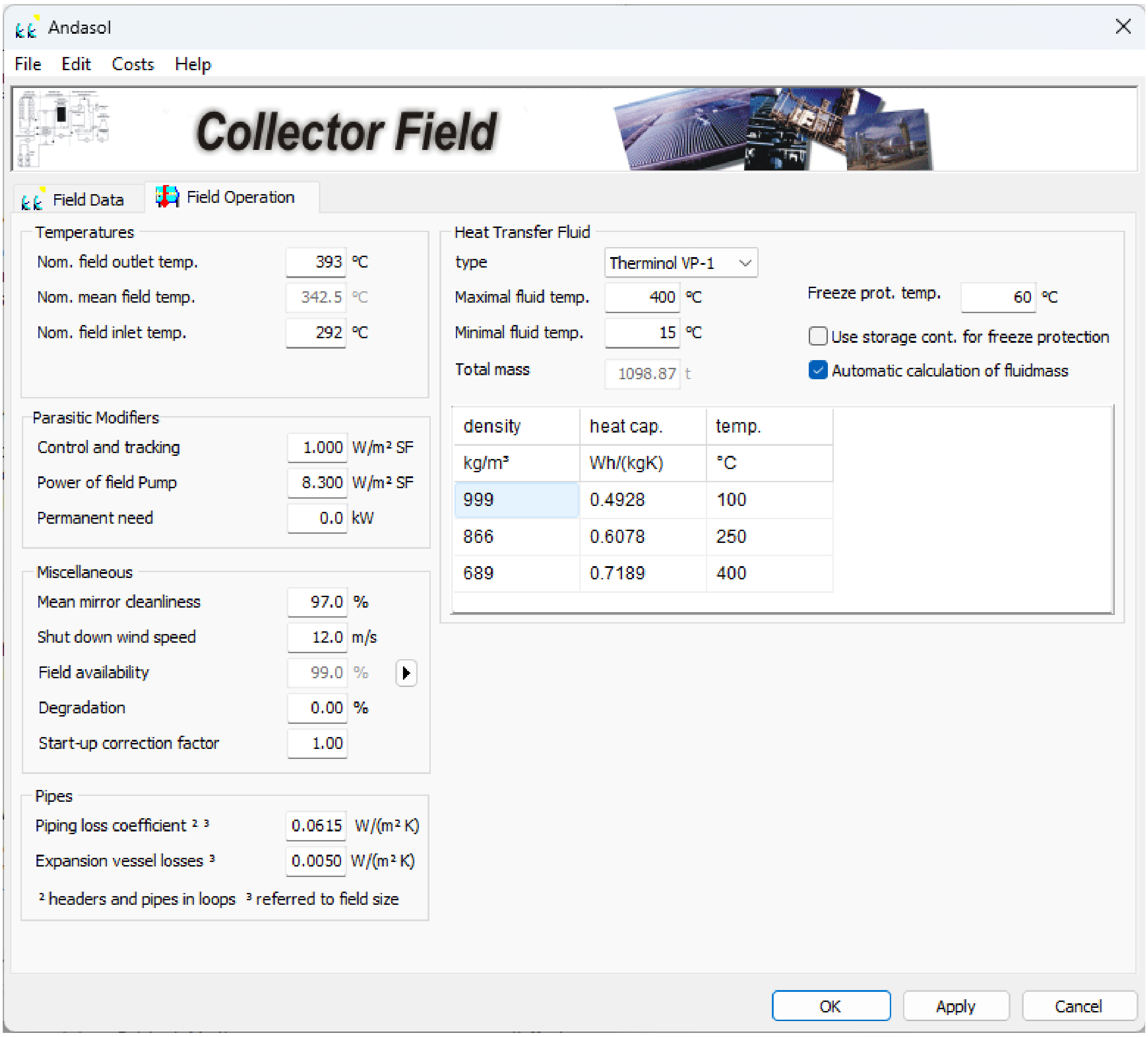
The parameter *Land Use* is only important for economic calculations. When applying changes of the collector field form **greenius** checks whether the field dimensions matches with the used land. If it does not, a warning message is displayed. It is the result of multiplying the field size by the land use factor.

In the box *orientation* the distances between the collectors in one row and the rows themselves can be set. The *distance between rows* is used to determine row to row shading losses. For parabolic trough collectors this value should be about three times the aperture width. For Fresnel collectors the row distance can be less. The *distance between collectors* can be important if the box *End gain possible* is checked. In this case end losses are reduced because concentrated radiation crossing the focal line beyond the end of the collector are absorbed by the absorber tube of the next collector.

Tracking axis tilt angle is usually not relevant for concentrating collector fields since line focus collectors are usually not designed for tilted installation. However you can define a tilt value of the tracking axis between 0° and 90° where 0° is the default value for a horizontal tracking axis. The *tracking axis azimuth* is more important for concentrating systems since it is sometimes not possible or intended to build the collectors in exact north-south orientation. The tracking axis azimuth default value is 0° (south). Positive values refer to orientations towards the west (clockwise), and negative values towards the east. For a horizontal tracking axis (tilt = 0°) there is no difference for the incidence angles between e.g. azimuth = 90° and azimuth = -90°, but if the collector is tilted (tilt > 0°) incidence angles will change significantly between 0° and 90° azimuth orientation. A collector with -90° azimuth is oriented towards the east and will therefore have smaller incidence angles when the sun stands in eastern directions.

Field Operation

The second tab *Field Operation* contains parameters like temperatures and flow rate of the heat transfer fluid. The *nominal field inlet temperature*, *nominal field outlet temperature* are important for the performance calculation since they have a large impact on thermal losses and start-up times. As long as the calculated field outlet temperature is lower than the nominal outlet temperature, **greenius** assumes that the solar field is in heat up mode and the power block is not operating.



The *Field operation* tab allows the definition of specific parasitic loads of the solar field in W_{el} per m² of aperture area. The parasitic loads are divided into 3 parts, the first part is called *control and tracking* and covers all parasitic consumption for solar field tracking, measurement and control.This is a constant value which is needed once the solar field is in operation (the main HTF pumps are working).

The second value of the solar field parasitic loads is for the main field pumps and the specific value given here is used to calculate the nominal pumping power according to:

$$P_{el,SF,nom} = A_{field,net} \cdot p_{el,spec}$$

The solar field parasitics for off-design operation are then calculated by scaling these nominal parasitics with the solar field actual output.

$$P_{el,SF} = P_{el,SF,nom} \left(\frac{Q_{out,SF}}{Q_{out,SF,nom}} \right)^2$$

The third value is used to calculate the permanent need of the plant. It refers to the consumers that use electricity when the plant is in operation, but also when it is not in operation, such as lighting or air conditioning.

In the box *Miscellaneous* comprises several parameters defining the performance of the solar field. The *mean mirror cleanliness* is accounted as constant factor in calculation of the solar field efficiency. The default value of 97% can be used as a first guess. However, cleanliness depends strongly on the location and washing strategy.

Beyond the *shut down wind speed* the collector is in stow position in order to protect the mirrors and the heat output is zero.

The *field availability* is a constant factor of the solar field efficiency. By clicking the small triangle the availability can be modified in detail in the availability form.

The *degradation* parameter is a simple way to account for performance losses of the solar field over life time without simulating each single year of operation. Instead the solar heat and electricity output in year i of operation is calculated using

$$Q_i = Q_{TOY} \cdot \left(1 - x_{degradation}\right)^i$$

where $x_{degradation}$ is the user defined degradation parameter in the form and Q_{TOY} the electricity or heat output of the simulated typical operation year.

The *start-up correction factor* is used for the start-up modelling of the solar field. The energy need to heat up the field and reach the nominal temperature is multiplied by this factor. In this way, the high impact of the start-up consumption on the energy yield.

Further loss parameters defined on this form are specific heat losses for the piping and the expansion vessel. Piping means headers as well as all pipes within the loops except for the absorber tubes since their thermal losses are defined on the *collector assembly* form. The specific piping and vessel losses are referred to the net aperture area of the solar field and the temperature difference between HTF and ambient. The HTF temperature used here is a weighted average based on the pipe and header lengths defined in the tab *field data*.

Several *heat transfer fluids* (HTF) can be chosen. Maximum and minimum fluid temperatures are given for information purposes. The freeze protection temperature is relevant for the field simulation. In order to prevent freezing of the HTF the temperature is always hold above the defined freeze protection temperature which should be above the minimum fluid temperature. If the box *Use storage content for freeze protection* is checked the required heat is taken from the thermal storage. If not, a fossil auxiliary boiler is used. In the ASCII files the fluid type is represented by an integer value ID. Please refer to the table below to get the appropriate identifier. Air is currently not allowed as HTF for trough technology.

ID	Heat Transfer Fluid
1	Therminol VP-1
2	DOWTERM A
3	SYLTERM 800
4	Water (fluid)
5	Water/steam
6	Solar Salt
7	Hitec Salt

ID	Heat Transfer Fluid
8	Air
9	Helisol XLP

Available Field Models

The user can choose between a simple and an enhanced model in the collector field form. The major difference is that the simple model calculates with an average solar field temperature while the enhanced one divides the collector loop into 14 nodes.

The assumptions of the simple model are valid as long as the temperature profile over the loop is linear and the temperature level is not too high. Therefore the enhanced model was first developed for direct steam generation where the temperature can be constant over the majority of the loop length. High HTF temperatures lead to non-linear effects that are not comprised by the simple model. Therefore the enhanced model is currently adapted for single-phase fluids in order to provide more exact results for parabolic troughs with molten salt as HTF. Please note, that external steam table DLLs are required for the calculation of direct steam generation!

Since heat losses as well as fluid properties are temperature dependent, an iterative procedure is necessary to solve the collector balance equations, or the heat losses and fluid properties may be calculated determining the temperature dependent data using temperatures of the preceding time step. For the simple solar field model the second approach is used. In order to minimize errors caused by this approach, each hour is divided further into up to 30 time steps in case of large temperature gradients. This ensures that the temperature used for heat loss and fluid properties calculation is close to the actual temperature of this time step. For the enhanced model a non-linear solver is used anyway. Therefore the temperatures of the current time step can be used without additional effort.

The results from the simple model and the enhanced model are typically not identical because of non-linear temperature effects but the difference in annual thermal or electrical output shall be within a few percentage points, provided that the parameters for both models are identical and the system design and operation is reasonable. Particularly the maximal fluid mass flow rate for the enhanced model can be a reason for large deviations in the results of both models. If this parameter is too small, it will cause a huge amount of dumping in summer due to the upper temperature limit of the heat transfer fluid.

Thermal Storage

Currently, there are two different models for thermal storages available in **greenius**: One is called *Single tank* and the second is called *Two tank molten salt*. The main difference between both models is the treatment of thermal losses. While the thermal losses of a 2-tank molten salt storage are constant, they depend on the storage content for the other storage model.

In contrast to the two available *models* for thermal storages, there are four different storage *types* available in the drop down menu in the upper part of the form. The Two tank molten salt and the Single Tank refer to the corresponding model mentioned above. The third type is a concrete storage to be used within a power tower using air as heat transfer fluid. Currently this storage type relies also on the single tank model, but a more refined model could eventually be implemented in the future. The last storage type is an electric storage which can obviously not be used as thermal storage. Please refer to Electric Storage (Battery) for more details on electric storages.

The main parameters which have to be defined by the user are capacity as well as the heat and pumping losses. The number of possible full load hours and the field excess are calculated automatically depending on the collector field parameters. Due to the differences in both models the input windows of both storage types differ slightly.

Two-Tank Molten Salt Storage Model

Almost all of the parabolic trough CSP plants with thermal storage are currently using the 2-tank molten salt storage type with a hot salt tank at temperatures of about 380°C and a cold storage tank at about 290°C. The heat is stored by cycling the molten salt between both tanks and a series of heat exchangers is used to transfer the sensible heat from the HTF to the salt during the charging period and back to the HTF during the discharging period. Since the salt mixture used in these tanks solidifies at about 220°C both tanks must always kept hot, which is the explanation for the almost constant heat losses. CFD calculations published by [Sch08] are confirming this approach.

The **greenius** user has to define the net storage capacity as well as the maximum charging and discharging power which may be different since the salt pumps have a volume flow rate limit and the usable temperature difference is typically lower at discharging mode.

Thermal losses must be defined by giving a value of fractional losses in 24h based on the net storage capacity. For large thermal storage tanks as in the following figure the assumption of 1% per 24h might be a reasonable estimate but relative losses are increasing if the storage volume decreases.

Temperature differences for charging and discharging as well as pumping parasitics must be defined as electrical power per thermal power. In general, pumping parasitics are accounted during charging *and* discharging of the storage. However in certain cases, where the same fluid is used as heat transfer fluid and storage medium, pumping parasitics are only accounted for discharging, because the solar field recirculation or receiver pumps are used to pump the fluid directly to the storage. For the following combinations of storage types and HTFs parasitics are only accounted during discharge operation:

Technology	**Storage Type**	**HTF**
All technologies based on trough field	Two tank molten salt	SolarSalt or Hitec
All technologies based on solar tower	Two tank molten salt	SolarSalt or Hitec
All technologies based on non-concentrating collectors	Single Tank	All HTFs

The molten salt storage model needs the minimal storage content for the simulation. The actual value of this parameter has no large impact on the simulation results and so it may be set more or less arbitrarily. 10 to 20% of the net storage capacity would be a reasonable estimate for the minimal storage content.

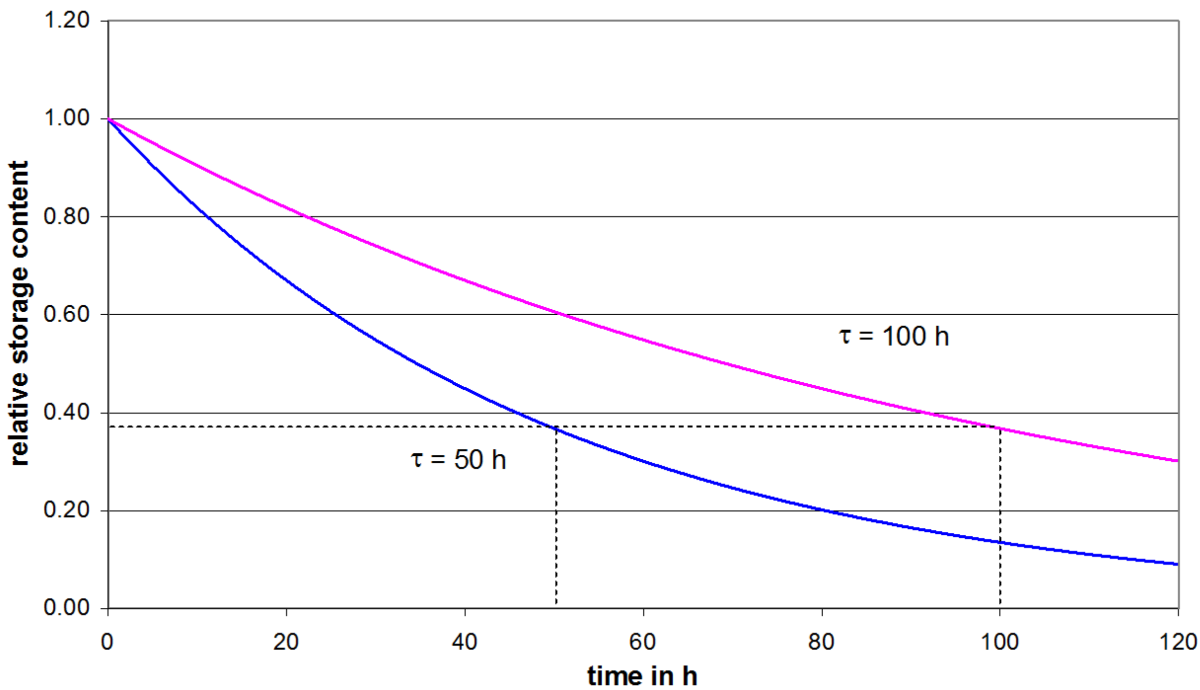
The minimal storage content is only important to account for the constant thermal losses even in times when the storage is “empty”. Normally at the load curve/solar driven operating strategy the storage is only loaded if the field produces excess heat above the demand respectively rated power. As explained above, molten salt storage has constant heat losses which might cause the storage content to fall below the minimal content, particularly in winter season when the solar field does not deliver excess heat for longer time periods. The implemented and hard coded operation strategy for the molten salt storage in **greenius** is: charging the storage up to the minimal content has the highest priority among all options, since freezing must be prevented in any case. This energy cannot be used for electricity production but it is dissipated to the environment.

The implemented strategy for parabolic trough plants with storage is as follows: If the solar field cannot cover the demand respectively rated power, heat is taken from the storage. If this heat is not sufficient the power block uses the parallel fossil fired heater if the plant has such a device.

Single Tank Storage Model (Storage Types "Single Tank" and "Concrete")

This storage model is **not** a thermocline storage as one could assume but it uses a different approach for the thermal losses. They are proportional to the storage content and the actual value is defined by a time constant.

The time constant is used to calculate the thermal losses of the storage. It is defined as time interval (in hours) needed for the thermal storage content to decrease down to 1/e = 36.8% of the initial content due to thermal losses to the ambient. The following figure shows the storage content for 2 different time constants.



At the load curve/solar driven operating strategy the storage is only loaded if the field produces excess heat above the demand respectively rated power. If the solar field cannot cover the demand respectively rated power, heat is taken from the storage. If this heat is not sufficient the power block uses the parallel heater if possible.

Boiler

An auxiliary boiler must be defined by the user for those cases when a certain load curve is required and the auxiliary heat is needed to fulfil this load demand even in times when the heat delivered by the solar field and/or the thermal storage is not sufficient.

When no auxiliary boiler is loaded or the nominal power of the auxiliary boiler is 0, solar-only operation mode is assumed by default!

The auxiliary boiler is defined by nominal power, fuel net calorific value and boiler efficiency. It is assumed that the boiler does provide the heat at the same temperature level as the solar field like e.g. a HTF heater does. When the auxiliary heater is a real boiler with the capability to produce live steam at higher temperature/pressure (with the aim to run the power block at higher efficiency in fossil mode) this must be considered in the power block lookup table.

Fuel price and specific emissions have to be given as input as well as specific parasitic consumption in electricity consumption per heat produced.

Powerblock

In contrast to most of the other components, the *power block* input form shows the main nominal values of this part of the plant, but cannot be edited. Instead, new power block components should be defined directly in the `*.gpa` file. All part load performance parameters are stored in lookup tables in this file. The composition of these lookup tables is described below.

The power block form also contains scaling parameters in order to modify the power block size and/or efficiency. Using the scaling parameters is an easy way to simulate bigger power plants without creating a completely new power block file. The three modifiers are effective in the following sense:

- The *scale factor* changes all values from the lookup tables like heat input, electrical output, parasitics etc. by the same factor.
- The *turbine efficiency modifier* changes the generator output leaving heat input and parasitics unchanged.
- The *parasitics efficiency modifier* does only affect the parasitics and leaves the heat input and gross electric output at their original values.

Two different electrical losses may be defined within the form. The *Transformation loss* accounts for all losses during transformation from medium voltage (delivered by the generator) to high voltage (used for feed-in to the grid). *Transmission losses* may be defined separately. Both losses are simple loss factors multiplied with the net output of the plant in order to calculate the electricity delivered to the grid.

The parameter *Maximal load* defines the capacity of the power block relative to the design thermal input, which is shown as first value in this box. Whenever the solar field thermal output is higher than *solar thermal input* multiplied by *maximal load*, heat must be redirected to an optional thermal storage or dumped.

Furthermore the following coefficients in the box *parasitic modifiers* can be set:

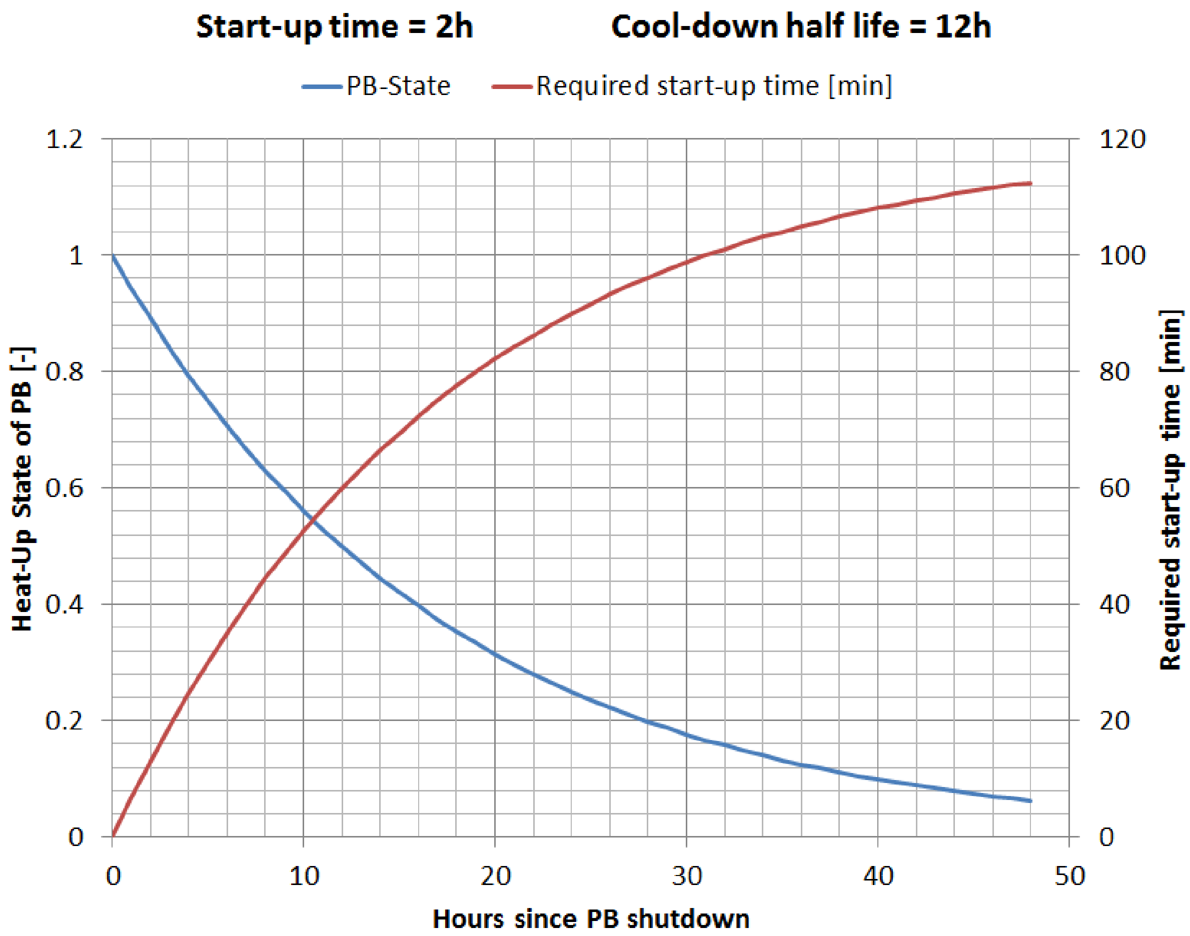
- Parasitics for the auxiliary heater (only relevant if the lookup table `auxiliary_heat` contains non-zero values)
- Cooling parasitics

The auxiliary heater can be defined in the power block lookup tables. In this case the corresponding parasitics can be defined by this parasitic modifier. If there is no auxiliary heat lookup table defined, this parasitic modifier is neglected. It is usually not reasonable to use the separate auxiliary boiler component and the auxiliary heat lookup table in the power block component the same time. The definition of cooling parasitics makes only sense if they are not included in the parasitics lookup table of the power block. The auxiliary heater parasitics are relative to the auxiliary heater output and the cooling parasitics are based on the electrical gross output of the power block.

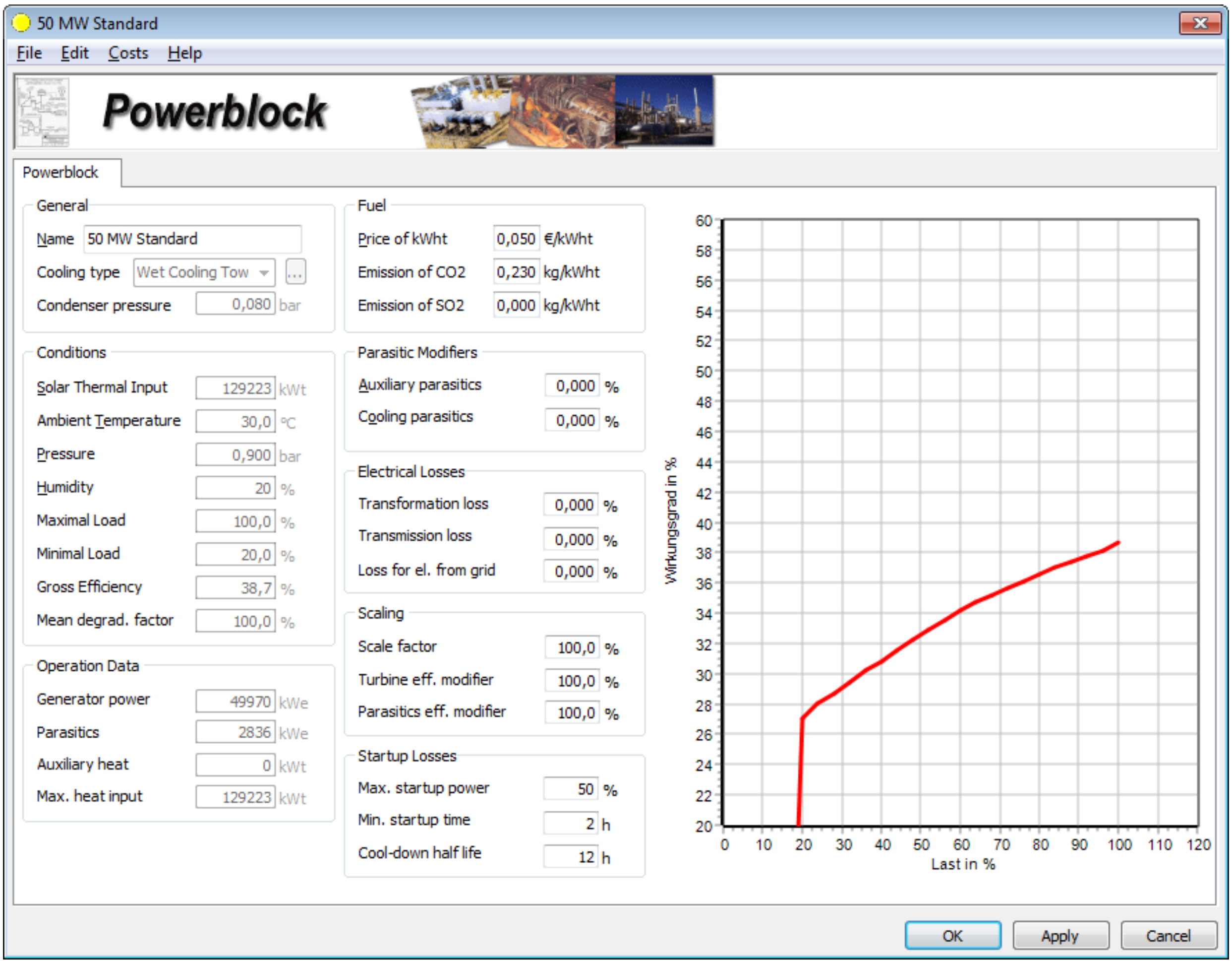
The power block component includes two parameters for *Transformation losses* from medium voltage to high voltage and *Transmission losses* from the site to the grid connection point. Both parameters are accounted as simple factors.

Heat losses during startup can be modeled using the two parameters *Max. startup power* and *Min. startup time*. The fraction given for max startup time refers to the thermal input at 100% load. From a technical point of view it is not possible to heat up the turbine and corresponding gear with 100% thermal input in order to respect the maximum temperature gradients. The *min. startup time* is the time needed for a cold start after >24 hours of downtime when *max. startup power* is available for heatup. If less heat is supplied to the power block the startup process will take longer, accordingly.

Whenever the power block is not operating it cools down according to Newton's cool-down law (exponential function) defined by the *cool-down half life*. The figure below shows a typical cool-down curve of a power block with 2 hours start-up time and a cool-down half life of 12 hours for the first 48 hours after stop of operation. In this example, a start-up after a shut-down of 8 hours would take about 44 minutes. Those values are quite realistic for bigger steam turbines with 50MW rated power and above. However, both parameters, *start-up time* and *cool-down half life* depend strongly on the size,live steam pressures and overall design of the used turbine. Please consult the manufacturer of the used turbine.



The graph on the right hand side of the power block form shows the dependency of the power block efficiency on load for nominal ambient conditions.



The menu entry Costs opens the component costs window. The power block costs are defined separately from the solar field costs.

Composition of Lookup-Tables

The power block in **greenius** is defined as lookup table in the corresponding `*.gpa` file. Commercial heat balance calculation programs such as Ebsilon Professional, IPSEpro, or GateCycle may be used to generate these tables. Alternatively the performance maps can be delivered by power block providers. **greenius** contains some standard steam turbine cycles. They can be scaled to other power values and efficiencies as a first approximation as long as no other detailed performance data is available (see above).

Lookup tables are used for the data transfer between an externally modelled power block and **greenius**. Therefore, a separate table must be defined for all output values such as output power, secondary heat demand (auxiliary boiler output) and parasitics. The dimensions of a matrix are equal to the number of degrees of freedom. Usually, **greenius** has seven degrees of freedom:

- Thermal input power
- Inlet temperature
- Ambient air pressure
- Ambient temperature

- Relative ambient humidity
- Condenser pressure
- Required electricity output (in hybrid or storage operation mode)

The following matrices are processed

- Generator output power
- Parasitics
- Secondary heat demand
- HTF advance temperature
- HTF reverse temperature

The process matrices can be defined in a given text format and imported by **greenius**.

Format of the Matrix Header

The lookup table starts with a header that follows the conventional parameter definition at the beginning of the `*.gpa` power block file.

The dimensions of the process matrices are defined in the header. This is done by the identification of the supporting points for the parameters. The following table summarizes the possible

Input Parameter	**Unit**	**Identifier**
Thermal Input Range	kW_{th}	`thermal_input_range`
Inlet Temperature Range	°C	`inlet_temperature_range`
Amb. Temperature Range	°C	`amb_temperature_range`
Amb. Pressure Range	bar	`amb_pressure_range`
Amb. Humidity Range	% rel. humidity	`amb_humidity_range`
Condenser Pressure Range	bar	`condenser_pressure_range`
Load Range	kW_{el}	`load_range`

For each parameter one separate line is used for the definition. It starts with an identifying key word which is followed by the supporting points for this parameter. The number of supporting points can be freely chosen and values do not need to increase linearly. For instance, the following definition is possible:

```
thermal_input_range      0     10000      15000      17000
18000      19000      19500      20000
```

It must be noticed that **greenius** only interpolates linearly. If the resolution of the matrices is to low, this can cause some deviations. The highest and the lowest coordinates are interpreted by **greenius** as limiting values. Values above these limits are set to the limit during the simulation.

With these headers all six degrees of freedom can be defined. If a degree of freedom is not used, a single supporting point is sufficient, e.g.

```
amb_pressure_range       0.8
```

Then, **greenius** performs all calculations for the power block with the given value as described for the limits above; in the given example only for an ambient pressure of 0.8 bar.

The coordinate “-1” for the required generator output indicates that there are no requirements by the grid operator. This is the so-called *free load case*, where all available power can be fed into the grid.

After the definition of the coordinates the design point of the power plant is defined in a separate line. The syntax for this identification is:

```
design_conditions   97000.00  20.00     0.80 60.00     0.08 -
1.00
```

The coordinates of the matrices for the design point are given here. The order of the values is equal to the order of the definition of the coordinates. In the example above the design conditions are valid for a solar heat of 97 MW_{th} at an ambient temperature of 20°C, ambient pressure of 800 mbar, relative air humidity of 60 %, condenser pressure of 80 mbar and the free load case.

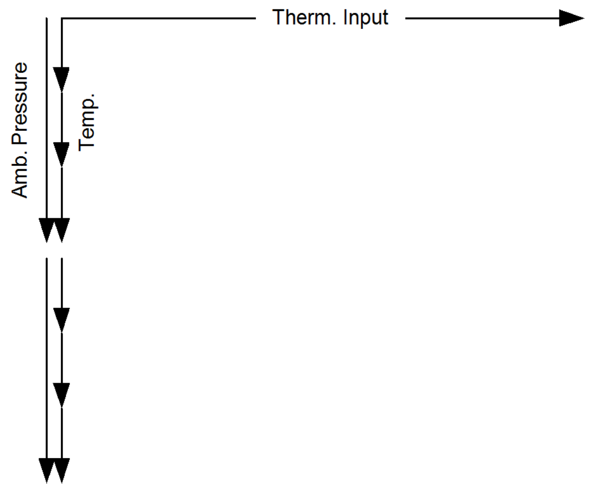
Format of the Lookup Tables

Below the header the lookup tables themselves are defined. The table below summarizes the different matrices that can be defined:

Output	**Unit**	**Identifier**
Generator Output	kWe	`generator_output`
Parasitics	kWe	`parasitics_matrix`
Auxiliary Heat	kWth	`auxiliary_heat`

HTF Inlet Temperature	°C	`HTF_inlet_temperature`
HTF Outlet Temperature	°C	`HTF_outlet_temperature`

The data of the matrices is given two-dimensional. Normally, the x-axis is the thermal input power. The y-axis gives series values depending on the order of the other coordinates. The following figure shows the axis order for the two dimensions *ambient air temperature* and *pressure*.



For the following header

```
thermal_input_range0    2000 …    120000
amb_temperature_range   20
amb_pressure_range 0.8
amb_humidity_range 60
condenser_pressure_range      0.04 0.05 0.06 0.07 0.08 0.09 0.1
load_range     -1.00     0.00 10000.00  20000.00  30000.00
40000.00
```

the resulting definition of the data for the generator output is:

```
Thermal Input range:     0        2000     4000     6000     8000     10000    12000    14000    16000
Amb. Temperature range: 20
Amb. Pressure range:     0.8
Amb. Humidity range:     60
Condenser Pressure range:         0.04     0.05     0.06     0.07     0.08     0.09     0.1
Load range:      -1.00   0.00     10000.00          20000.00          30000.00          40000.00

Design conditions:       97000.00          20.00    0.80     60.00    0.08     -1.00

Generator Output
         0.00    175.4190178      638.2883573       1116.650522       1611.024075       2121.94494
         0.00    163.2019181      612.6706848       1078.08236        1560.002447       2059.016508
         0.00    179.2254041      607.2593868       1053.834455       1519.753752       2005.855206
         0.00    165.5687184      585.7876021       1024.328335       1481.989763       1959.605562
         0.00    153.809738       568.4170548       1000.582012       1451.048135       1920.590434
         0.00    116.8818471      533.1929664       965.657038        1414.9008         1881.575307
         0.00    108.1244237      518.105949        944.2846157       1387.300324       1847.818256
         0.00    0.00     0.00    0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00
         0.00    0.00     0.00    0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00
         0.00    0.00     0.00    0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00
         0.00    0.00     0.00    0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00
         0.00    0.00     0.00    0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00
         0.00    0.00     0.00    0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00
         0.00    0.00     0.00    0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00
         10000.00         10000.00          10000.00          10000.00          10000.00          10000.00
         10000.00         10000.00          10000.00          10000.00          10000.00          10000.00
         10000.00         10000.00          10000.00          10000.00          10000.00          10000.00
         10000.00         10000.00          10000.00          10000.00          10000.00          10000.00
         10000.00         10000.00          10000.00          10000.00          10000.00          10000.00
         10000.00         10000.00          10000.00          10000.00          10000.00          10000.00
         10000.00         10000.00          10000.00          10000.00          10000.00          10000.00
         20000.00         20000.00          20000.00          20000.00          20000.00          20000.00
         20000.00         20000.00          20000.00          20000.00          20000.00          20000.00
         20000.00         20000.00          20000.00          20000.00          20000.00          20000.00
         20000.00         20000.00          20000.00          20000.00          20000.00          20000.00
         20000.00         20000.00          20000.00          20000.00          20000.00          20000.00
         20000.00         20000.00          20000.00          20000.00          20000.00          20000.00
```

Since the ambient conditions are only one-dimensional, the first real y-dimension is the dimension of the condenser pressure. The seven coordinates of the condenser pressure define seven lines of data for the generator output depending on the x-dimension of the thermal input power. The figure above shows clearly that the matrix consists of groups of seven lines. Every group belongs to the demand of the grid. (The first seven lines belong to the coordinate -1 (= free load), the next seven lines to the coordinate 0 kW, the next seven lines to 10000 kW and so on).

Parabolic Troughs for Process Heat

This technology is similar to the *Parabolic Trough Power Plant with Storage* technology. It uses the same input windows for *Collector Assembly*, *Collector Field* and *Thermal Storage* and *Boiler*. The process heat technology has no power block and the heat consumer is not explicitly defined since there is wide variety of potential consumers. A load curve may be defined by the user and in case that a boiler is also defined, **greenius** tries to fulfil the load curve by using heat from solar field, storage and boiler (in this order).

The following components exist for parabolic trough power plants:

- Trough collector
- Trough field
- Thermal storage
- Boiler

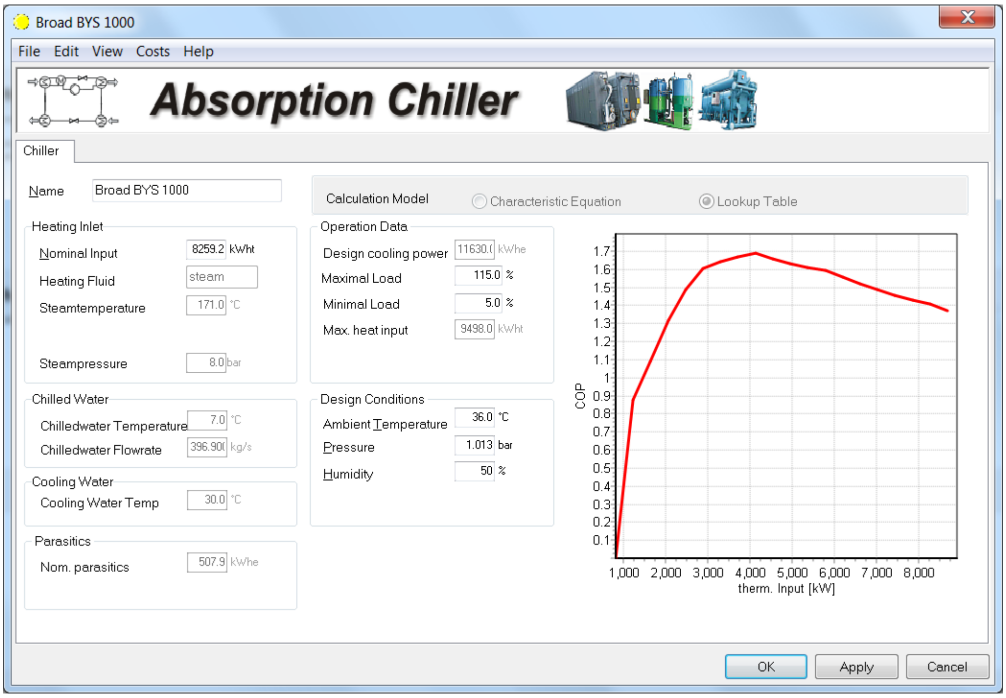
Parabolic Troughs for Chilling

This technology is very similar to the *Parabolic Troughs for Process Heat* and to *Parabolic Trough Power Plant with Storage* technology. It uses the same components *Collector Assembly*, *Collector Field, Thermal Storage* and *Boiler*. The Chiller component is new for this technology.

Two-Stage Chiller

A model for the 2-stage, steam driven chiller is available for usage together with Parabolic Trough field as heat source. It is different from the single-stage chiller for non-concentrating technologies.

The chiller input form contains only the main nominal values, which cannot be edited, and a visualization of the part load behaviour of the COP and the cooling power. The performance is stored in a separate lookup table in the `*.gpa` file.



On the left hand side the process parameters (temperature, mass flow rate and pressure) are shown for the three external fluid streams under nominal conditions, the *heating fluid inlet stream*, the *chilled water* and the *cooling water stream*. Furthermore the value nominal parasitics is shown, including the electrical consumption of the pump set (chilled water and cooling water pump), the power demand for the cooling tower and the machine room, and the consumption of internal pumps of the chiller.

As operational data the nominal cooling power is shown, and the percentage of maximum and minimum load, with the corresponding maximum heat input. Also displayed are the design conditions as Ambient Temperature, Pressure and Humidity.

The 2-stage Chiller in **greenius** is mainly defined by lookup tables, which contain manufacturer's data. The lookup tables are similar to the lookup tables of the power block. It is possible to add new machines, using given manufacturer's data, performance data or results from a detailed thermodynamic simulation.

The lookup table model bases on matrices that link the performance values (output values) of the chiller to the operational and ambient conditions (input parameters).

For the chiller, five input parameters are used:

Input Parameter	Unit	Identifier
Thermal input power	kW_{th}	`thermal_input_range`
Ambient air pressure	°C	`amb_pressure_range`
Ambient temperature	bar	`amb_temperature_range`
Relative ambient humidity	% rel. humidity	`amb_humidity_range`
Required cooling output (Load)	kW_{th}	`load_range`

Two output matrices are processed by **greenius**:

Output	Unit	Identifier
Cooling power	kW_{th}	`cooling_power`
Parasitics	kW_{el}	`parasitics_matrix`

The matrices must be defined in ASCII text format in order to be interpreted correctly by **greenius**. Please refer to the section on lookup tables in the power block component to learn about the correct definition of the matrices in the `*.gpa` file.

Power Towers

The power tower system allows the annual performance simulation of central receiver solar power plants. The plant is defined by three components: Tower system (comprising heliostat field, central receiver and tower), thermal storage and power block. **greenius** versions below 4.3.1 had separate heliostat field and receiver components. But since the designs of receiver and heliostat field depend on each other, both parts cannot be changed separately any more.

The following components exist for tower power plants:

- Tower system
- Thermal storage
- Powerblock

The thermal storage and power block components are the same as for trough technology with the above mentioned exception for the storage type in tower systems with air as HTF.

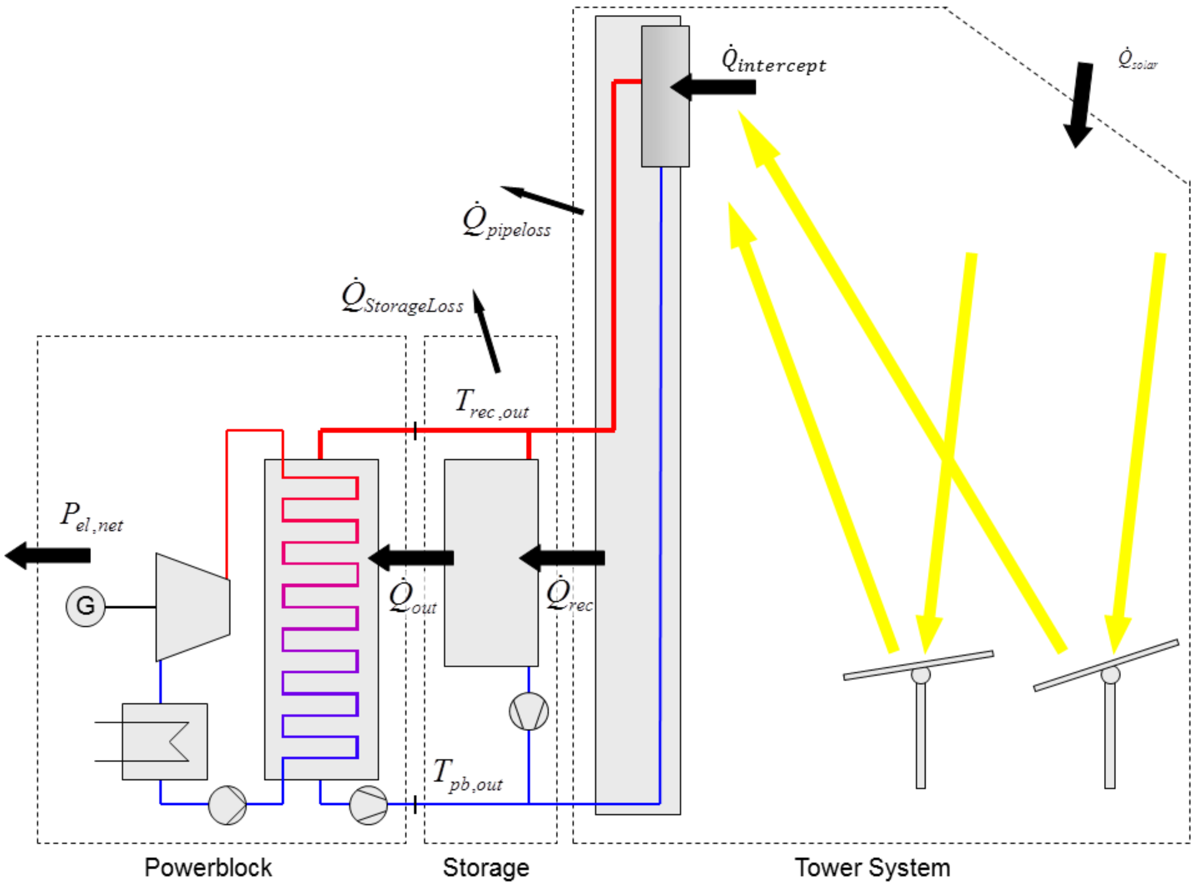
Tower System

Starting with **greenius** version 4.3.1 the *Tower System* component combines the former individual components tower field and tower receiver. The combination of receiver and heliostat field into one single component reduces the potential for wrong dimensioning of heliostat field and receiver. Even though both field and receiver have their individual efficiency lookup tables they are not independent from each other regarding their technical design. For example, the efficiency of a solar field depends significantly on the design of the corresponding receiver, whether it is a cavity or an external receiver. Nevertheless, both subcomponents, Heliostat Field and Central Receiver are described in separate subsections.

For the economic evaluation of solar tower plants a third subcomponent, the tower, is relevant. The costs of all three sub components may be edited via *Costs|View Costs*. There are no technical parameters to be set for the tower sub component.

Energy flow model

The following graphic shows the heat balance formulation used for these components:



The performance of tower field, receiver, and power block is described by lookup tables. The thermal storage is a time-delay element, which relies on simple energy accumulation of thermal energy and allows the modeling of thermal losses.

The calculation of tower field and receiver can be described by

$$\dot{Q}_{rec} = \eta_{rec} \cdot \eta_{TowerField} \cdot \dot{Q}_{solar}.$$

Thus, the lookup tables for these two components contain the respective efficiencies. Additionally, piping losses can be included for the receiver.

The tower model can be used for the two heat transfer fluids (HTF) molten salt and air. Even though the technical design of a power plant using air as HTF is very different from the one of a molten salt plant, both systems can be modelled in the same way from an energy-based perspective. Technically, a molten salt plant delivers its complete heat output to the storage, from where a separate pipe feeds hot salt to the steam generator of the power block. With an air-receiver the hot air flow is divided behind the receiver. One part is directly fed to the steam generator of the power block while the other is used to heat up the storage. In **greenius** energy balances are calculated in the same way for molten salt and air systems. As single difference molten salt tower systems can only be combined with *two-tank molten salt storages*, while air receivers require a *Single Tank Storage*.

The power block model contains several lookup tables and calculates the net electrical energy, which is produced by the plant:

$$\dot{Q}_{el,net} = f(\dot{Q}_{out}, T_{rec,out})$$

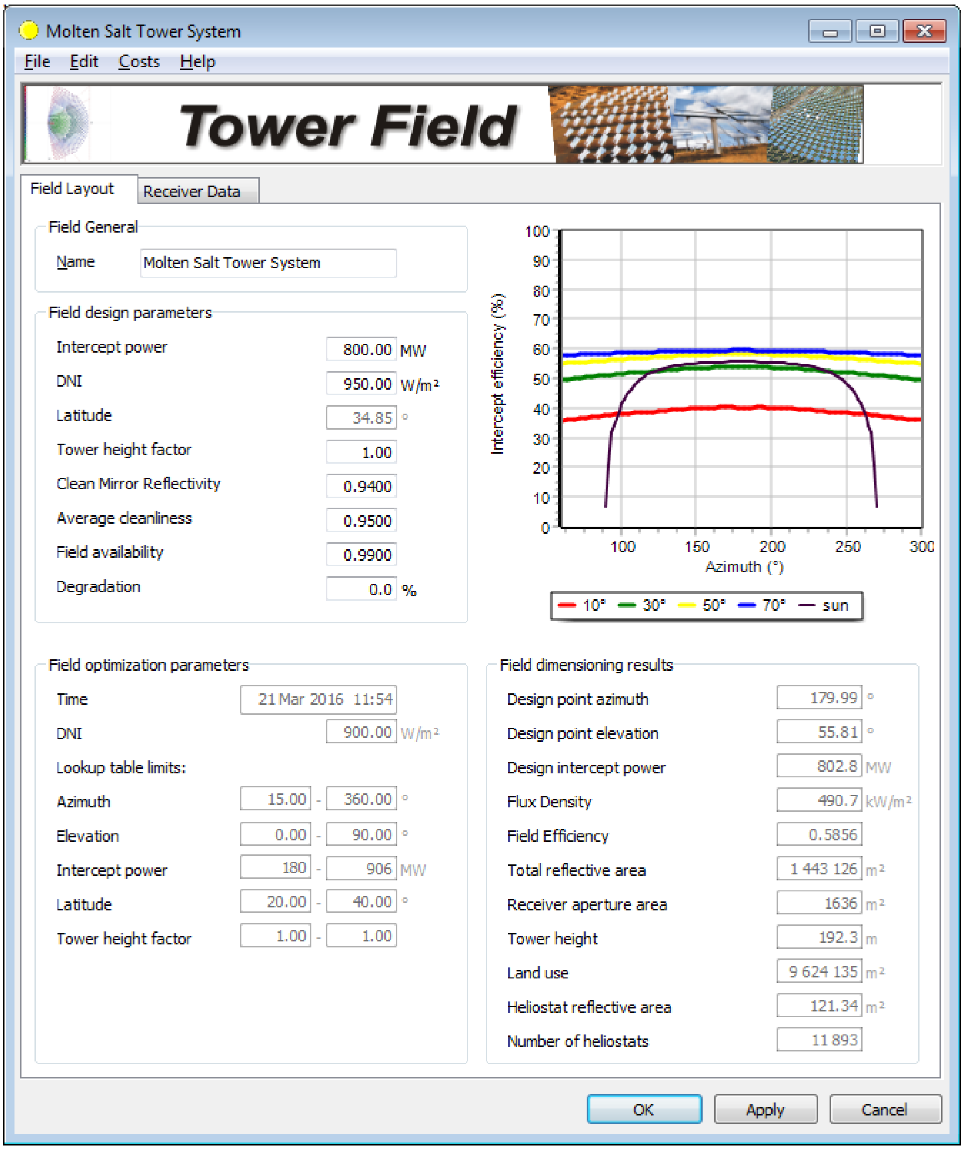
Heliostat Field

The heliostat field (tower field) model is based on lookup tables. The efficiency lookup table (also referred to as efficiency map) required for the simulation of tower systems must be calculated using external software such as *HFLCAL* [Sch09]. It is not possible to modify the lookup tables for field and receiver within **greenius**. Instead, you can create your own maps by modifying the existing or creating new ASCII files using a text editor of your choice. The syntax of those ASCII files is similar to that of the Powerblock component and also described below. **greenius** comes with default tower system files for molten salt and air as HTF which are based on *HFLCAL* calculations. The corresponding efficiency maps of those default configurations cover a wide intercept power range and are therefore suitable for many projects.

Heliostat Field Parameters

The *heliostat field* tab of the tower system form shows three major groups of values. The *field design parameters* can be altered by the user and are used to define the design of the heliostat field, mainly its size. The *field optimization parameters* are given for informational purpose. They give additional information on the parameters used for the field optimization and the lookup tables. The *field dimensioning results* are based on the user input and summarize the heliostat field properties.

The following screenshot shows the heliostat field tab of the tower system form:



A diagram visualizes the performance of the specified field. The coloured lines illustrate the field efficiency at different sun elevation angles. The black line shows the efficiency of the field on the design day, tracking the suns actual elevation for the given azimuth.

Field design parameters

Only values in this group can be modified by the user while all other groups only yield additional information:

- The *intercept power* is the solar irradiation power entering the receiver aperture at design conditions. This value is not equal to the power reflected by the heliostat field due to atmospheric attenuation and spillage (irradiation missing the receiver aperture). The value is displayed in red if it exceeds the range defined by the efficiency map. Please note that this may be the case even if the intercept values is within the range displayed as intercept power range in group Field optimization parameters because the ranges of the efficiency map are valid for 100% reflectivity, cleanliness and availability as well as for the stated field optimization DNI. Usually, reflectivity, cleanliness and availability below 100% result in slightly bigger heliostat fields in order to reach the user defined nominal intercept power.
- The *DNI* is the direct normal irradiation on the heliostat field at design conditions. Smaller

design DNI values lead to bigger solar fields.

- The site *latitude* is taken from the Location component
- The tower height cannot be set directly by the user since it is a parameter which is usually defined during the field optimization process. However, the efficiency maps provided with greenius include data for lower (e.g. tower height factor 0.7) as well as higher (e.g. tower height factor 1.3) towers. The *tower height factor* allows you to modify the tower height within the given range. Default value is 1.0.
- The parameters *clean mirror reflectivity*, *average cleanliness* and *field availability* account for imperfect optical properties and soiling of the mirrors as well as unavailable heliostats (e.g. due to technical issues or maintenance).
- The *degradation* factor allows to account for degradation of the mirrors over the life time of the plant. The value defines the annual reduction of the thermal output of the tower system. A value of 1% means that the thermal output is reduced each year by 1% compared to the preceding year. For a degradation of 1% the thermal output in year 25 would be only 78.6% (=0.99^24) of the first year output.

The relevant ASCII-Identifiers for the parameters of this group:

```
user_design_heat_intercept         800
user_design_dni      950
user_design_tower_height_factor          1
user_clean_mirror_reflectivity           0.94
user_mirror_cleanliness        0.95
user_field_availability        0.99
user_degradation          0
```

Field optimization parameters

The *Field Optimization Parameters* group is only shown for informational purposes and contains data about the optimization parameters used during the calculation of the heliostat field lookup table:

- The field optimization *time* for tower systems is usually solar noon of March 21. If other points in time are defined, **greenius** only uses the given date and ignores the time. Instead, dimensioning calculations are always performed for solar noon.
- The *DNI* value used for the field optimization is relevant for the actual size of the heliostat field required to reach the desired intercept power. If deviating design DNI values are defined in group *field design parameters* **greenius** automatically scales the heliostat field accordingly.
- The *Lookup table limits* represent the parameter ranges for which the efficiency map is defined. They should be respected when defining the design values for *intercept power*, *tower height factor* and site *latitude*. If **greenius** is forced to evaluate efficiency maps for out-of-range values the closest value within the range is used instead. There is **no extrapolation** implemented!

The relevant ASCII-Identifiers for the parameters of this group:

```
design_timedate      42450.4959360757
design_DNI      900
azimuth_range   0    15   45   75   105  135  165  180  195
225   255  285  315  345  360
```

```
sunheight_range 0    5    15   25   35   45   60   75   90
latitude_range  20   30   40
heat_intercept_range 179.8     450.6     906.3
tower_height_factor_range 1
```

Field dimensioning results

Whenever the user changes an input value, a design calculation is performed. The *field dimensioning results* group shows the corresponding results for design conditions:

- The *design point azimuth* and *elevation* are the calculated values for solar noon on the day shown as *time* in the *field optimization parameters* group.
- The *design intercept power* is the actual intercept power at design conditions. It can differ slightly from the user defined value due to interpolation within the efficiency table and accounting for user defined DNI, reflectivity, cleanliness and availability values.
- The *flux density* is the solar flux at the receiver aperture corresponding to the intercept power (design intercept power divided by receiver area)
- The shown *field efficiency* value includes the impact of user defined *clean mirror reflectivity*, *cleanliness* and *availability*.
- The *total reflective area* is the total surface of the mirrors in the heliostat field and defined by a lookup table in the ASCII file.
- The *receiver aperture area* is defined by a lookup table in the ASCII file.
- The *tower height* at tower height factor 1.0 is defined by a lookup table in the ASCII file. The user can alter the tower height using the *tower height factor* if supported by the lookup table.
- The *land use* is defined by a lookup table in the ASCII file.
- The *heliostat reflective area* is the surface of a sinlge heliostat defined by a lookup table in the ASCII file.
- The *number of heliostats* is calculated based on the total reflective area and the heliostat reflective area.

Since the shown values are results of the design calculation they are not saved in the ASCII file. Nevertheless, the lookup tables are defined in the ASCII file and described below.

Heliostat field efficiency map and lookup tables

Since external software is used to optimize the heliostat field for the tower system, efficiency maps and lookup tables are a reasonable way to define the required input data for **greenius**. For complete heliostat field definition, **greenius** expects in total six lookup tables for the following parameters:

- Field efficiency
- Total reflective area
- Receiver aperture area
- Land use

- Tower height
- Heliostat area

The lookup tables are defined at the end of the ***.gpa** file in the same way as for the power block lookup tables. The lookup table for the field efficiency is also called efficiency map and has five dimensions:

1. Azimuth of the sun
2. Elevation of the sun
3. Latitude of the corresponding location
4. Design point heat intercept
5. Tower height factor

Please note that the efficiency map contains values at 100% reflectivity, 100% cleanliness and 100% availability! Those factors are accounted separately within **greenius**. An exemplary lookup table for the field efficiency is shown below (not all columns and rows shown!):

```
azimuth_range   0   15  30  45  60  75  90  105 120 135 150 165 180 195 210 225 240 255 270 285 300 315 330 345 360
sunheight_range 0   5   15  25  35  45  60  75  90
latitude_range  20  30  40
heat_intercept_range    179.8   450.6   906.3
tower_height_factor_range   1

field_design_conditions 180 60  30  350 1

total_field_efficiency
    0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0
    0.3119  0.3124  0.3182  0.3233  0.3228  0.3351  0.3461  0.3519  0.3556  0.3684  0.3751  0.3756  0.3769  0.3749  0.3767  0.3
    0.4452  0.4467  0.4544  0.4597  0.4639  0.4786  0.4959  0.5028  0.5102  0.5243  0.5343  0.5362  0.5366  0.5361  0.5348  0.52
    0.5539  0.5555  0.5659  0.5697  0.5761  0.5917  0.6134  0.6193  0.6289  0.6425  0.6556  0.6553  0.6567  0.6554  0.6557  0.6
    0.6286  0.6291  0.6353  0.6414  0.6498  0.6628  0.6787  0.6876  0.6981  0.7093  0.7183  0.7214  0.7241  0.7214  0.7184  0.7
    0.6769  0.6759  0.6795  0.6864  0.6944  0.7048  0.7172  0.7262  0.7361  0.7451  0.7511  0.7552  0.7589  0.7552  0.7511  0.7
    0.7195  0.7196  0.7220  0.7266  0.7327  0.7402  0.7487  0.7553  0.7623  0.7681  0.7725  0.7754  0.7772  0.7754  0.7725  0.7
    0.7549  0.7559  0.7569  0.7593  0.7624  0.7664  0.7706  0.7740  0.7774  0.7804  0.7825  0.7835  0.7839  0.7835  0.7825  0.7
    0.7802  0.7802  0.7802  0.7802  0.7802  0.7802  0.7802  0.7802  0.7802  0.7802  0.7802  0.7802  0.7802  0.7802  0.7802  0.7
    0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0
    0.3035  0.3051  0.3131  0.3198  0.3211  0.3360  0.3497  0.3573  0.3640  0.3809  0.3878  0.3892  0.3895  0.3885  0.3894  0.3
    0.4316  0.4344  0.4452  0.4527  0.4593  0.4776  0.4978  0.5075  0.5196  0.5381  0.5500  0.5514  0.5520  0.5514  0.5506  0.5
    0.5373  0.5401  0.5530  0.5593  0.5688  0.5881  0.6130  0.6224  0.6365  0.6542  0.6694  0.6697  0.6710  0.6698  0.6696  0.6
    0.6121  0.6129  0.6205  0.6290  0.6402  0.6565  0.6762  0.6887  0.7027  0.7169  0.7280  0.7327  0.7361  0.7328  0.7281  0.7
    0.6617  0.6611  0.6658  0.6745  0.6850  0.6983  0.7137  0.7258  0.7384  0.7498  0.7577  0.7636  0.7678  0.7636  0.7578  0.7
    0.7074  0.7077  0.7110  0.7170  0.7248  0.7343  0.7449  0.7536  0.7624  0.7700  0.7758  0.7800  0.7822  0.7800  0.7759  0.7
    0.7462  0.7474  0.7488  0.7519  0.7559  0.7609  0.7662  0.7706  0.7750  0.7788  0.7817  0.7835  0.7842  0.7835  0.7817  0.7
    0.7755  0.7755  0.7755  0.7755  0.7755  0.7755  0.7755  0.7755  0.7755  0.7755  0.7755  0.7755  0.7755  0.7755  0.7755  0.7
    0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0
    0.2913  0.2907  0.2922  0.3111  0.3194  0.3432  0.3567  0.3735  0.3848  0.4044  0.4097  0.4213  0.4277  0.4207  0.4107  0.4
    0.4073  0.4071  0.4125  0.4296  0.4466  0.4740  0.4987  0.5204  0.5422  0.5682  0.5831  0.5955  0.6029  0.5954  0.5834  0.5
    0.4956  0.4982  0.5078  0.5240  0.5447  0.5742  0.6055  0.6293  0.6539  0.6818  0.7004  0.7115  0.7164  0.7115  0.7004  0.6
    0.5614  0.5643  0.5740  0.5894  0.6104  0.6368  0.6646  0.6889  0.7120  0.7345  0.7514  0.7620  0.7662  0.7620  0.7514  0.7
```

The residual five lookup tables contain design data of the heliostat field which is independent from the current sun's position. Therefore **those lookup tables are defined as if the first two dimensions azimuth and elevation had only one single node**! Due to the reduced number of effective dimensions the lookup tables much shorter single column arrays:

```
reflective_area
    254213
    254820
    255063
    695132
    697680
    703503
    1505007
    1527461
    1538142
```

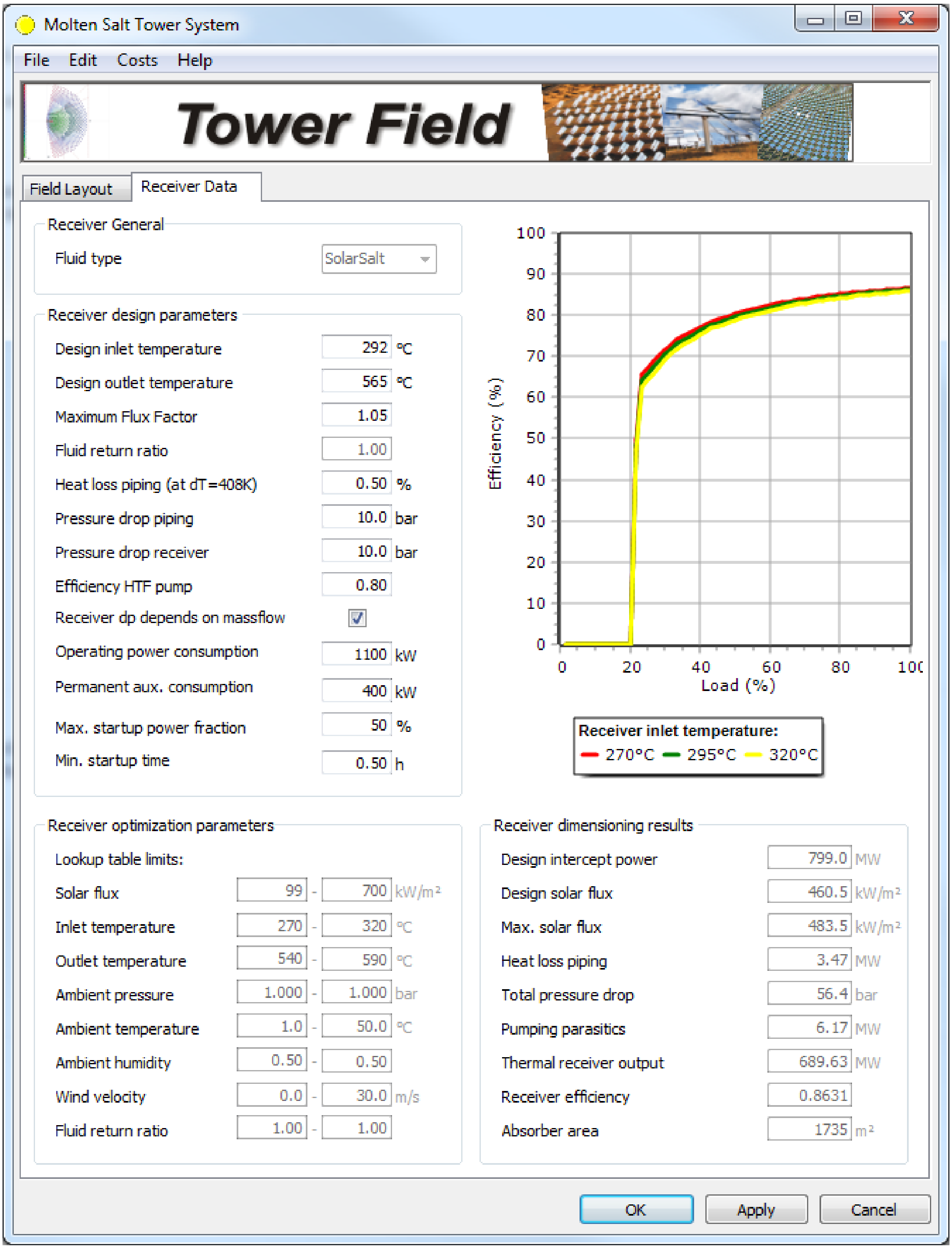
Central Receiver

The receiver is located on the top of the tower and is supposed to transfer the irradiated solar energy to the heat transfer fluid (HTF). The gathered heat can be used to supply energy to the thermal storage and/or the power block. Within **greenius** the receiver model is based on a lookup table.

Receiver Parameters

The *receiver* tab of the tower system form shows three major groups of values. The *receiver design parameters* can be altered by the user and are used to define the major properties of the receiver, e.g. inlet and outlet HTF temperatures. The *receiver optimization parameters* are given for informational purpose. They give additional information on the parameters used for the receiver optimization and the lookup tables. The *receiver dimensioning results* are based on the user input and summarize the receiver properties.

The following screen shot shows the receiver tab of the tower system form:



A diagram visualizes the efficiency of the receiver at different receiver inlet temperatures.

The fluid type cannot be changed by the user within **greenius**, but in the ASCII file via an integer value. Please note that only SolarSalt, Hitec Salt and Air are allowed as HTFs for the tower system model.

ID	Heat Transfer Fluid
1	Therminol VP-1

ID	Heat Transfer Fluid
2	DOWTERM A
3	SYLTERM 800
4	Water (fluid)
5	Water/steam
6	Solar Salt
7	Hitec Salt
8	Air

Receiver design parameters

The user may specify the following values of the receiver:

- *Design inlet temperature* - This value is only used to calculate the design efficiency. The inlet temperature used for individual time instances during annual calculations is obtained from the power block return temperature.
- *Design outlet temperature* - Specifies the mean temperature, at which the receiver delivers the heat transfer fluid to the power block and/or thermal storage. The receiver is continuously operated at this temperature, as long as sufficient DNI is available.
- *Maximum flux factor* - This factor allows the operation of the receiver at flux densities higher than the design flux density specified above. Choose a value of 1.0 if the receiver shall only be operated up to the design solar flux stated in group *receiver dimensioning results*. Note that the value is displayed in red if the corresponding allowed solar flux maximum exceeds the definition ranges of the lookup table.
- *Fluid return ratio* - For open receiver technologies (air as HTF), the return ratio can be specified to define the fraction of fluid which re-enters the receiver. For closed systems (molten salt as HTF) this value is 1.0 and cannot be edited by the user.
- *Heat loss piping* - Allows the implementation of piping heat losses between receiver and storage / power block if these are not included in the receiver lookup-table. The loss is defined as a fraction of the receiver heat output. The underlying dT is mentioned in the form. It is calculated as difference between the mean receiver temperature (0.5 * (T_inlet + t_outlet)) at field optimization (lookup table design conditions in ASCII file, not necessarily the same as defined by the user in the form) and the ambient temperature. For the annual simulation heat losses are calculated in the same way using the nominal outlet temperature, the HTF return temperature from the power block (depends on load level) and the ambient temperature.
- *Pressure drop piping* - The nominal pressure drop at design mass flow in the piping between storage / power block and receiver that must be overcome by the HTF pump. The actual pressure loss for a given time step depends on the load level of the receiver and is scaled quadratically:

$$\Delta p = \Delta p_{nom} \cdot \left(\frac{\dot{m}}{\dot{m}_{nom}}\right)^2$$

- *Pressure drop receiver* - The nominal pressure drop at design mass flow in the receiver.

- *Efficiency HTF pump* - The efficiency of the HTF pump is accounted when calculating the pumping parasitics of the tower system.
- *Receiver dp depends on mass flow* - If this box is checked the pressure drop in the receiver is scaled quadratically as for the piping pressure drop. Otherwise the pressure drop remains constant at design value over all load levels.
- *Operating power consumption* - The electrical power required for piping and receiver when they are in operating mode (all power consumption, except for pumping power). This power consumption is considered constant for all time steps when the receiver is operating.
- *Permanent auxiliary consumption* - The electrical power needed by the system in each time step regardless of the operating mode
- *Maximal startup power fraction* - The maximal solar power which can be sent to the receiver during start up (given as fraction of the nominal receiver thermal output). This parameter, together with *Minimal startup time* below may be used to consider start up losses of the tower system.
- *Minimal startup time* - The minimal time needed for heat up, provided that the maximal start up power is used. (Minimal start up power * Minimal start up time = start up energy). Cooling down of the system is modelled with a simple approach: after 3 * minimal startup time the system is considered to be cold and the start up energy is required again. In between cooling down is assumed to be linear, which means that after 1 * minimal startup time without solar heat input, 33% of the start up energy is required.

Receiver optimization parameters

This variable group has informational purposes only and shows the definition ranges of the lookup table. User defined parameters in the receiver design parameters group are displayed in red colour if they exceed the definition ranges.

Receiver dimensioning results

This variable group shows the results of a design point calculation of the receiver. The values cannot be edited.

- *Design intercept power* - This value is copied from the solar field design point calculation.
- *Design solar flux* - This value is copied from the solar field design point calculation.
- *Max. solar flux* - Maximum accepted solar flux at receiver aperture derived from the user defined maximum flux factor and the design solar flux. This value should not exceed the definition range for solar flux of the lookup table.
- *Heat loss piping* - The piping heat losses at design conditions. The heat losses of the receiver itself are included in the efficiency lookup table.
- *Total pressure drop* - The total pressure drop is the sum of the pressure drop over piping and receiver as specified by the user and the geodetic pressure loss of the HTF between receiver and storage. For HTF air the geodetic pressure loss is neglected.
- *Pumping parasitics* - The pumping parasitics are calculated as described in the subsection below.

- *Thermal output* - The net thermal output of the receiver where piping heat losses are already subtracted.
- *Efficiency* - The receiver efficiency is calculated as thermal output divided by intercept power.
- *Design area* - Aperture area of the receiver. This value is copied from the solar field design point calculation

Model details

Parasitics

The parasitics of the tower system are calculated using

$$P_{parasitics} = \frac{\dot{m} \cdot \Delta p_{tot}}{\rho \cdot \eta_{pump}}$$

with:

$\dot{m}$	HTF mass flow
Δp_{tot}	Total pressure drop tower system
ρ	HTF density at receiver inlet temperature
η_{pump}	Efficiency of HTF pump

The total pressure drop is the sum of piping pressure drop, receiver pressure drop and geodetic pressure loss in the riser (HTF pipe from the bottom of the tower to the receiver in the top). Geodetic pressure losses cannot be neglected since the geodetic pressure gain in the downcomer cannot be recovered with current technology:

$$\Delta p_{tot} = \Delta p_{pipe} + \Delta p_{rec} + \Delta p_{geod}$$

$$\Delta p_{geod} = \rho \cdot g \cdot h$$

with:

g	Gravity
h	Tower height

Lookup table

The temperatures specified in the receiver form are defined at the boundary between receiver and storage respectively power block. These temperatures are not corrected for heat losses in the pipes!

The efficiency map has the following dimensions, which define the lookup table:

1. Solar flux - Average solar flux over the aperture area in kW/m²
2. Inlet temperature - Fluid temperature at the receiver inlet in °C

3. Outlet temperature - Fluid temperature at the receiver outlet in °C
4. Inlet enthalpy - Fluid enthalpy at the receiver inlet in kJ/kg
5. Outlet enthalpy - Fluid enthalpy at the receiver outlet in kJ/kg
6. Operating pressure - Pressure of the heat transfer fluid in bar
7. Ambient temperature - Given in °C
8. Return ratio - Given as a fraction between 0 and 1
9. Relative humidity - Given as a fraction between 0 and 1
10. Wind velocity at receiver height in m/s

The wind velocity at receiver height has an impact on receiver efficiency, depending on the actual receiver shape and technology.

The meteorological input file contains wind velocities at 10 m above ground but the receiver is installed at 150m or higher. Therefore the wind velocity from the meteorological data set is corrected by the wind profile power law. The corrected wind velocity is then used to calculate the receiver efficiency from the lookup table.

$$v = v_r \left(\frac{h}{h_r}\right)^{\alpha}$$

The exponent α (Hellmann exponent) is set to **0.143** assuming open land surface and neutral stability conditions.

Not all values are needed for all receiver technologies. The required values are listed in the following table (direct steam receiver not yet implemented):

	1	2	3	4	5	6	7	8	9
Air receiver	●	●	●				●	●	●
Direct steam receiver	●			●	●	●			
Liquid salt receiver	●	●	●						

The lookup table for the receiver efficiency is defined in the gpa file in the same way as for the power block lookup tables. While the single value parameters of the receiver are defined in the first section of the gpa file, the lookup table is located at the end of the file following the last lookup table of the heliostat field. An exemplary lookup table is shown below (not all rows included):

```
solar_flux_range     100 150 200 250 300 350 400 500 600 700
inlet_temperature_range 270 292 320
outlet_temperature_range     540 565 590
inlet_enthalpy_range     0
outlet_enthalpy_range    0
operating_pressure_range     1
ambient_temperature_range    1    50
return_ratio_range   1
relative_humidity_range 0.5
vwind_range 0    5    15   30

rec_design_conditions    560 292 565 0    0    1    25   1    0.5 5

receiver_efficiency
    0.6672  0.7559  0.8003  0.8271  0.8450  0.8579  0.8675  0.8811  0.8902  0.8967
    0.6544  0.7472  0.7938  0.8219  0.8407  0.8542  0.8643  0.8785  0.8880  0.8948
    0.6370  0.7356  0.7851  0.8150  0.8349  0.8492  0.8599  0.8750  0.8851  0.8923
    0.6458  0.7414  0.7893  0.8182  0.8375  0.8514  0.8618  0.8764  0.8862  0.8933
    0.6322  0.7322  0.7824  0.8127  0.8329  0.8474  0.8584  0.8737  0.8839  0.8913
    0.6136  0.7198  0.7731  0.8052  0.8267  0.8421  0.8537  0.8700  0.8808  0.8886
    0.6233  0.7262  0.7778  0.8089  0.8297  0.8446  0.8558  0.8716  0.8821  0.8897
    0.6087  0.7163  0.7704  0.8029  0.8247  0.8403  0.8521  0.8686  0.8797  0.8876
    0.5891  0.7032  0.7605  0.7950  0.8181  0.8347  0.8472  0.8646  0.8764  0.8847
    0.6669  0.7556  0.8001  0.8269  0.8448  0.8577  0.8673  0.8809  0.8900  0.8965
    0.6537  0.7467  0.7934  0.8216  0.8404  0.8539  0.8640  0.8783  0.8878  0.8946
    0.6360  0.7349  0.7845  0.8145  0.8345  0.8488  0.8596  0.8747  0.8849  0.8921
    0.6448  0.7407  0.7888  0.8177  0.8371  0.8510  0.8615  0.8762  0.8860  0.8930
    0.6309  0.7313  0.7817  0.8121  0.8324  0.8470  0.8579  0.8733  0.8836  0.8910
    0.6120  0.7186  0.7722  0.8045  0.8261  0.8415  0.8532  0.8695  0.8805  0.8883
    0.6217  0.7251  0.7769  0.8082  0.8291  0.8440  0.8553  0.8712  0.8818  0.8894
    0.6068  0.7150  0.7694  0.8021  0.8240  0.8397  0.8515  0.8681  0.8792  0.8872
    0.5868  0.7016  0.7593  0.7940  0.8173  0.8339  0.8465  0.8641  0.8759  0.8843
    0.6336  0.7333  0.7833  0.8135  0.8336  0.8480  0.8589  0.8742  0.8844  0.8917
    0.6201  0.7243  0.7766  0.8080  0.8291  0.8442  0.8555  0.8715  0.8821  0.8897
    0.6021  0.7122  0.7675  0.8008  0.8231  0.8390  0.8510  0.8678  0.8791  0.8872
    0.6127  0.7192  0.7726  0.8048  0.8263  0.8417  0.8533  0.8696  0.8805  0.8883
```

Dish/Stirling Systems

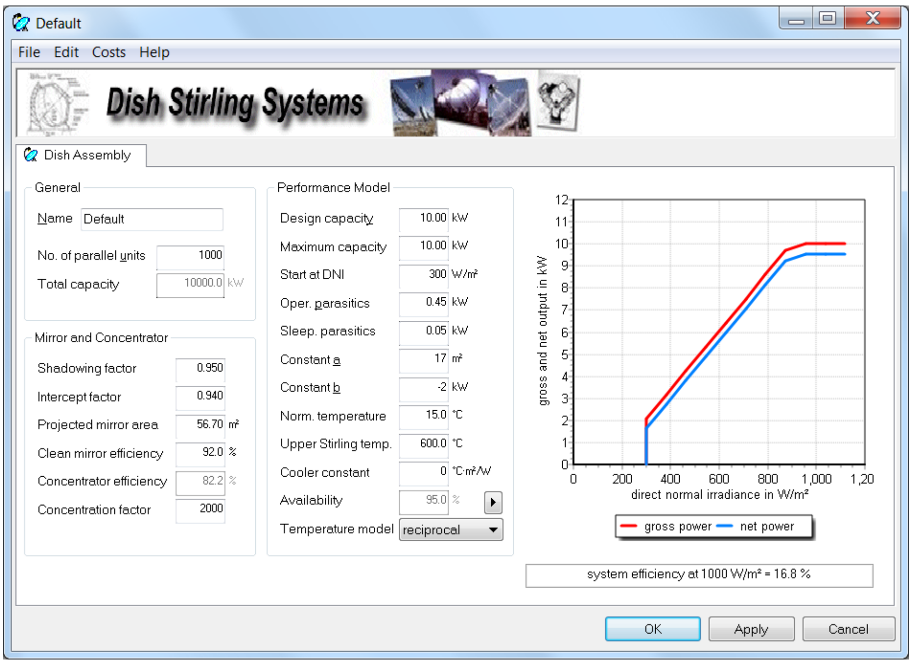
Dish-Stirling systems have only one component in **greenius** which defines all necessary input data. The parameters are described in the dish stirling component section.

Dish/Stirling Systems

The technical parameters of a Dish/Stirling-System are defined here. The parameters *projected mirror area* and *concentration factor* are for information only. All other parameters influence the performance model, which is described below. The graph showing the gross and net electrical output of one unit is updated instantly, when the performance parameters (except for parameters of the temperature correction) are modified.

The menu entry *Costs* opens the dish [costs input window](#).

Sleeping parasitics refers to the electricity consumption during none operating hours (hours with DNI lower than start DNI). This electricity consumption might be used for tracking.



Model equations:

Gross electrical performance:

$$P_{gross} = \begin{cases} a \cdot E_{cor} + b & \text{if} \quad E_{DNI} \geq E_{DNI,min} \\ 0 & \text{else} \end{cases}$$

E_{cor} : corrected irradiance in W/m²

E_{DNI} : direct normal irradiance in W/m²

$E_{DNI,min}$: minimal direct normal irradiance for starting generation in W/m²

a : performance model constant in W_e/(W/m²)

b : performance model constant in W_e

Corrected irradiance:

$$E_{cor} = E_{DNI} \cdot f_{ref} \cdot f_{temp}$$

f_{temp} : temperature correction factor

f_{ref} : reflection correction factor

Reflection correction factor:

$$f_{ref} = f_{shadowing} \cdot f_{intercept}$$

$f_{shadowing}$: shadowing and blockage factor

$f_{intercept}$: intercept factor

Temperature correction factor:

$$f_{temp} = \begin{cases} \dfrac{\vartheta_{norm,amb} + 273.15°C}{\vartheta_{amb} + f_{ref} \cdot E_{DNI} \cdot c_{cooler} + 273.15°C} & \text{reciprocal model} \\ \dfrac{\vartheta_{up,Stirling} - (\vartheta_{amb} + f_{ref} \cdot E_{DNI} \cdot c_{cooler})}{\vartheta_{up,Stirling} - \vartheta_{norm,amb}} & \text{Carnot model} \end{cases}$$

$\vartheta_{norm,amb}$: normalized temperature for performance model in °C

ϑ_{amb} : actual ambient temperature in °C

$\vartheta_{up,Stirling}$: upper Stirling temperature in °C

c_{ooler} : cooler constant in °C/(W/m²)

Parasitics:

$$P_{parasitic} = \begin{cases} P_{oper} & \text{for } E_{DNI} \geq E_{DNI,min} \\ P_{sleep} & \text{for } E_{DNI} < E_{DNI,min} \end{cases}$$

Power to/from the grid:

$$P_{grid} = P_{gross} - P_{parasitic}$$

P_{grid} : performance to/from the grid in W

P_{gross} : gross performance in W

$P_{parasitic}$: total parasitics in W

Process Heat according to ISO 24194

This technology is similar to the *Parabolic Troughs for Process Heat* technology. It uses the same input windows for thermal storage and boiler. The links below refer to the appropriate sections in the parabolic trough chapter. Input windows for collector and field are slightly different to those for Parabolic Troughs.

The following components exist for process heat:

- Solar collector
- Collector field
- Thermal storage
- Boiler

System Simulation

The heat output $\dot{Q}_{out}$ of the solar system is calculated using

$$\dot{Q}_{out} = \dot{Q}_{abs} - \dot{Q}_{heat} - \dot{Q}_{pipe}$$

with $\dot{Q}_{heat}$ as heat losses of the collector itself and $\dot{Q}_{pipe}$ as heat losses of the piping of the whole system. The corresponding equations can be found below.

The solar irradiation absorbed by the collector is

$$\dot{Q}_{abs} = n \cdot A_{collector} \cdot (E_{dir} \cdot \eta_{0,b} \cdot K_{dir} \cdot \eta_{shading} + E_{diffuse} \cdot \eta_{0,b} \cdot K_d)$$

where:

$$K_{dir} = IAM_{dir}(\theta)$$

In the case of using the EN 12975-2 standard, the following conversion is applied.

$$\eta_{0,b} = \frac{\eta_{0,hem}}{0.85 + 0.15 \cdot K_d}$$

The calculation of the direct irradiance E_{dir} and the diffuse irradiance E_{diff} on the collector is based on the meteorological values on the horizontal plane and uses the implemented algorithms in **greenius**. Shading of the horizon can also be considered in these calculations by using the shading Shading Editor.

Incidence Angle Modifier (IAM)

The angle of incidence on the collector is [Qua07]:

$$\theta = \arccos(-\sin\gamma_C \cos\gamma_s \cos(\alpha_s - \alpha_c) + \cos\gamma_C \sin\gamma_s)$$

For vacuum tube collectors the angle of incidence θ is divided into a longitudinal θ_l and a transversal angle of incidence θ_t referring the collector axis. According to [The85] the following formulas can be used:

$$\theta_l = |\gamma_C + \arctan(\tan(90° - \gamma_s) \cdot \cos(\alpha_s - \alpha_c))\,|$$

and

$$\theta_t = \left|\frac{\arctan(\cos\gamma_s \cdot \sin(\alpha_s - \alpha_c))}{\cos\theta}\right|$$

The incidence angle modifier for the direct irradiance IAM_{dir} Along of the vacuum tube collector is now defined by a longitudinal share $IAM_{dir,l}$ and a transversal share $IAM_{dir,t}$:

$$IAM_{dir}(\theta) = IAM_{dir,l}(\theta_l) \cdot IAM_{dir,t}(\theta_t)$$

For flat plate and concentrating collectors only the longitudinal incidence angle modifier $IAM_{\mathrm{dir,long}}$ is considered.

The angles α_S and γ_S describe the position of the sun according to DIN 5034 [DIN85] (α_S: 0°=N, 90°=E, 180°=S, 270°=W. γ_S: 0°=horizontal, 90°=vertical) and α_C and γ_C the orientation of the collector axis (α_C: 0°=S, 90°=W, 180°=N, 270°=E. γ_C: 0°=horizontal, 90°=vertical).

Heat Losses

The collector heat losses are calculated with the following formula, according to ISO 9806:

$$\dot{Q}_{heat} = n \cdot A_{collector} \cdot \begin{pmatrix} a_1 \cdot \Delta T + a_2 \cdot \Delta T^2 + a_3 \cdot v_{wind} \cdot \Delta T - a_4 \cdot (E_L - \sigma \cdot {T_a}^4) \\ +a_5 \cdot (dv_c/dt) + a_6 \cdot v_{wind} \cdot G + a_7 \cdot v_{wind} \cdot (E_L - \sigma \cdot {T_a}^4) + a_8 \cdot \Delta T^4 \end{pmatrix}$$

The collector heat losses are calculated with the following formula, according to EN 12975-2:

$$\dot{Q}_{heat} = n \cdot A_{collector} \cdot (a_1 \cdot \Delta T + a_2 \cdot \Delta T^2)$$

There are two methods for calculating heat losses in the piping: one based on the pipe length and another based on the area of the solar field. In both bases, the pipe losses are defined using the collector temperature ϑ_C and the ambient temperature ϑ_A.

Heat losses in the piping using the length-based method are calculated according to the following formula:

$$\dot{Q}_{pipe} = l_{pipe} \cdot k_{length} \cdot (\vartheta_C - \vartheta_A)$$

For the method based on the area of the solar field the following formula is used:

$$\dot{Q}_{pipe} = n \cdot A_{collector} \cdot k_{area} \cdot (\vartheta_C - \vartheta_A)$$

When starting heat transfer the collectors have to bring the whole system to design temperature. For this calculation the heat capacity of the pipes, the heat transfer fluid and the collectors are considered. When using ISO 9806 as the test method, the parameter a5 accounts for the heat capacity of both the collector and the fluid contained within it. However, for the piping, the heat capacity of the heat transfer fluid must still be considered separately.

Shading Losses

For the calculation of the shading losses, the following reference has been used: Bany, J.; Appelbaum, J.: The effect of shading on the design of a field of solar collectors, 1985. Let H_s be shaded length of the collector, l_{eff} the effective length of the collector subject to shading when there is a height difference with the next one, and $\eta_{shading}$ the shading efficiency. The following formulas have been used:

$$\eta_{shading} = 1 - \frac{n_{loops} \cdot n_{rows} - n_{unshaded\ rows}}{n_{loops} \cdot n_{rows}} \cdot \frac{H_s}{length_{collector}}$$

$$H_s = l_{eff} \cdot \left(1 - \frac{d_{row} + l_{eff} \cdot \cos(col_{elev})}{l_{eff} \cdot \left(\cos(col_{elev}) + \frac{\sin(col_{elev}) \cdot \cos(sun_{azim} - col_{azim} + 180°)}{\tan(sun_{heigth})} \right)} \right)$$

$$l_{eff} = length_{collector} - \frac{height_{difference}}{\sin(col_{elevation})}$$

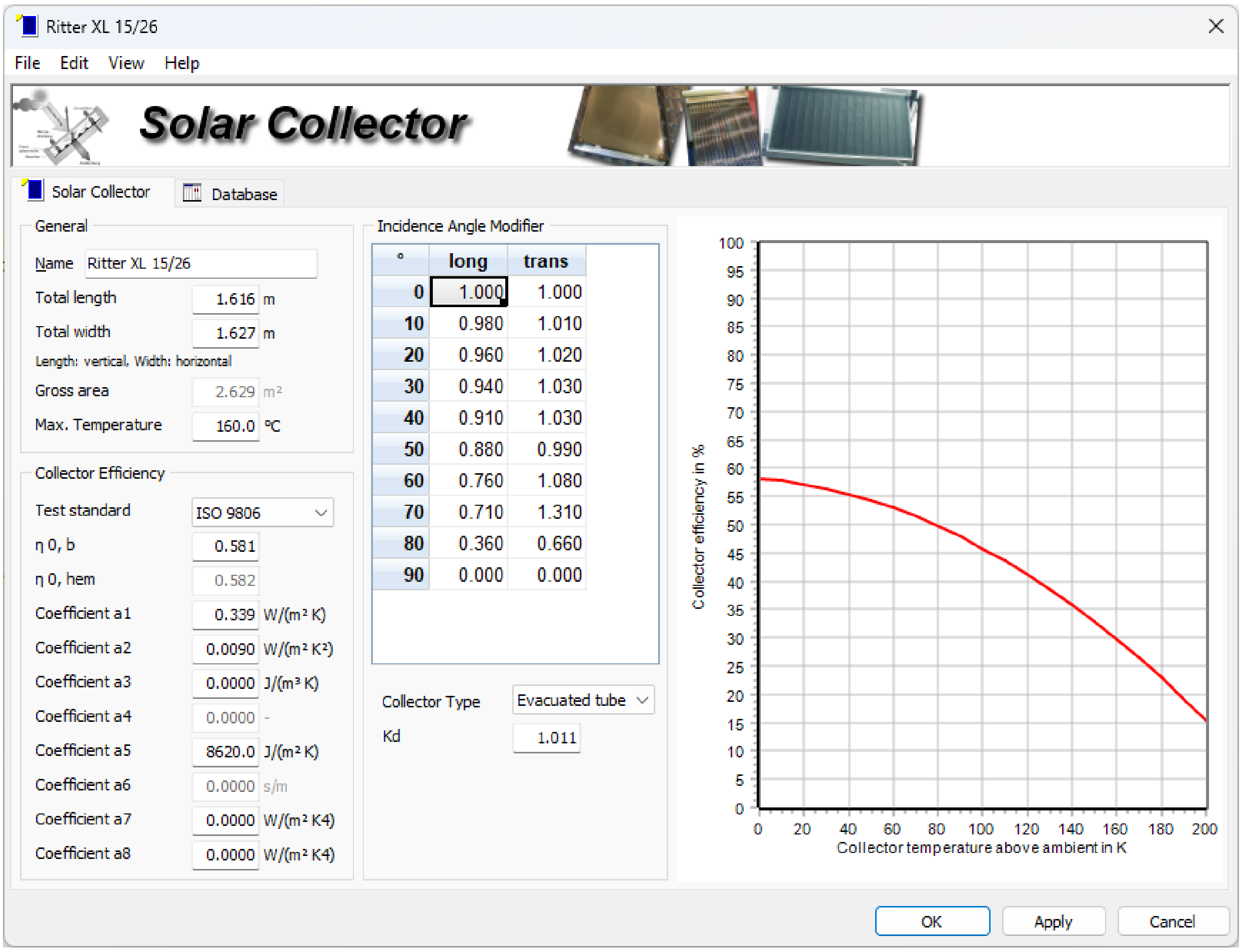
An additional 180 degrees is added to the difference between the azimuths of the solar field and the collector in the formula for H_s, as greenius takes azimuth 0 in the north direction and starts adding in a clockwise direction. Appelbaum and Bany take azimuth 0 in the south direction and also add in a clockwise direction.

ISO 24194 Collector

This input form is designed to enter specific parameters of solar collector which has been tested according to ISO/FDIS 24194. **greenius** comes with a file which is an excerpt of the Solar Keymark database and which contains specific parameters of about 2000 different collectors from this database.

The easiest way to use this data, is to switch to the "Database" tab on the same form, select a collector and transfer the data to the "Solar Collector" tab, as described below.

Three different collector types can be simulated: flat plate, evacuated tube, and concentrating collectors, provided that the required parameters are available.



General Parameters:

- Collector name
- Total length and total width
- Gross area
- Maximal temperature according to the manufacturer (Not all data sheets contain this value. In these cases, value is set to 199°C, by default.)

Collector Efficiency:

- Test standard: ISO 9806 or 12975-2
- Peak collector efficiency based on beam irradiance $\eta_{0,b}$
- Peak collector efficiency based on hemispherical irradiance $\eta_{0,hem}$
- Heat loss coefficient a1
- Temperature dependence of the heat loss coefficient *a2*
- Wind speed dependence of the heat loss coefficient *a3*
- Sky temperature dependence of the heat loss coefficient *a4: not active in greenius*
- Effective thermal capacity *a5*

- Wind speed dependence of the zero loss efficiency *a6: not active in greenius*
- Wind speed dependence of IR radiation exchange *a7*
- Radiation losses *a8*

Incidence Angle Modifier (IAM)

The direct IAM_{dir} is divided into a

- longitudinal incidence angle modifier $IAM_{dir,long}$ and a
- transversal incidence angle modifier $IAM_{dir,trans}$.

The resulting IAM is calculated as product of both using values from the table at the corresponding incidence angle.

The incidence angle modifier parameters are given in 10° intervals. This interval cannot be changed. Intermediate values are interpolated linearly using the table values.

Values for incidence angle modifiers may also entered by the user, if not imported from the Solar Keymark database.

The menu entry ■*Edit* offers some functions for the modification of the IAM table. Especially the interpolation function can be very useful if the IAM is not given in 10° steps. The available functions are:

- Delete all values (90°: IAM=1.0 and 0°: IAM=0)
- Interpolate empty cells linearly from neighbouring values
- Calculated for the angle range between 0 and 70° based on the user defined value at 50°

The IAM estimation based on the value at 50° uses the following equations:

$$IAM = 1 + b_0 \cdot \left(\frac{1}{\cos\theta} - 1\right)$$

$$b_0 = \frac{IAM(\theta = 50°) - 1}{\left(\frac{1}{\cos 50°} - 1\right)}$$

Visualisation

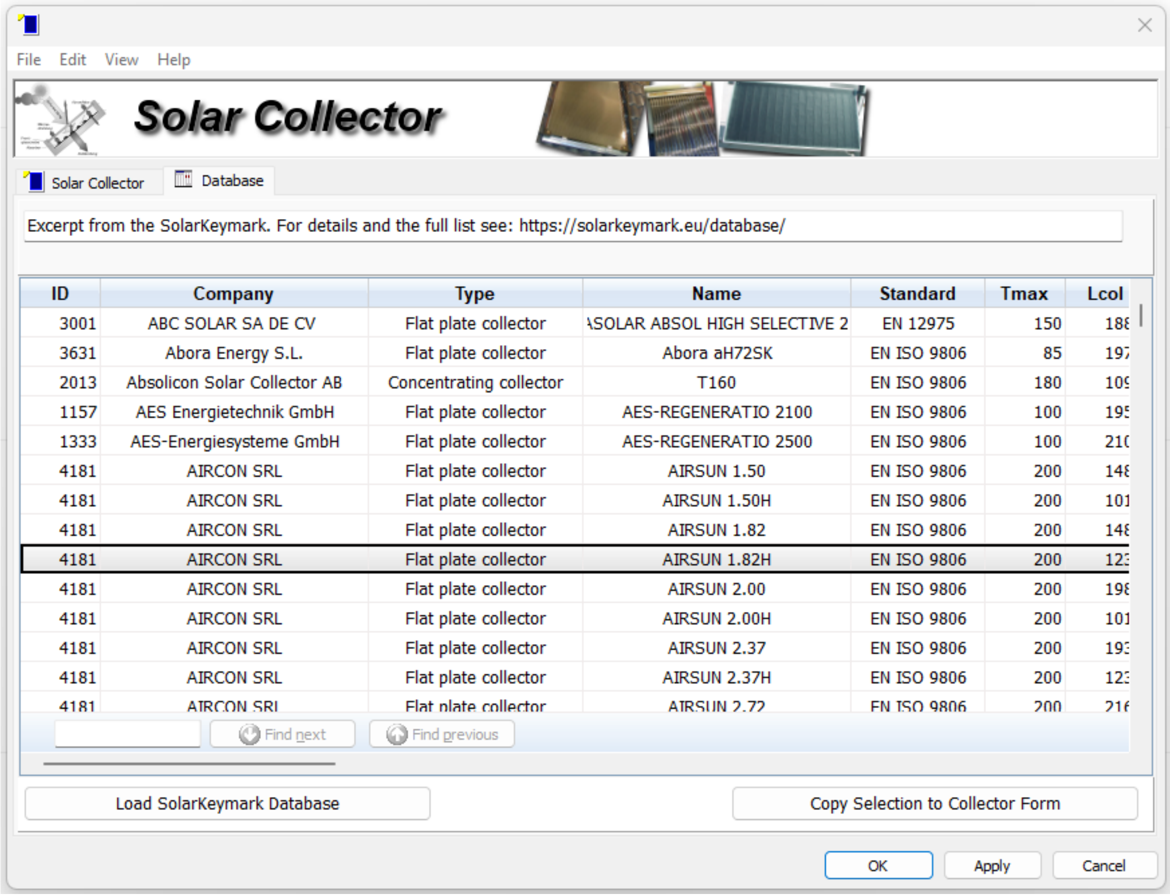
At the menu entry ■*View* two different types of graphics can be chosen. These graphics are calculated automatically using the current input parameters. When choosing ■*View|Collector Efficiency* the collector efficiency as a function of the difference ΔT between mean collector temperature and ambient is calculated according to ISO 9806 for a global irradiance of 1000 W/m².

The menu item ■*View|Incidence Angle Modifiers* shows the *IAM* as a function of the incidence angle. If the vacuum tube collector type is chosen the graph displays the longitudinal and the transversal incidence angle modifier. When choosing the flat plate collector type only the general incidence angle modifier is shown.

Importing collector data from the Solar Keymark database

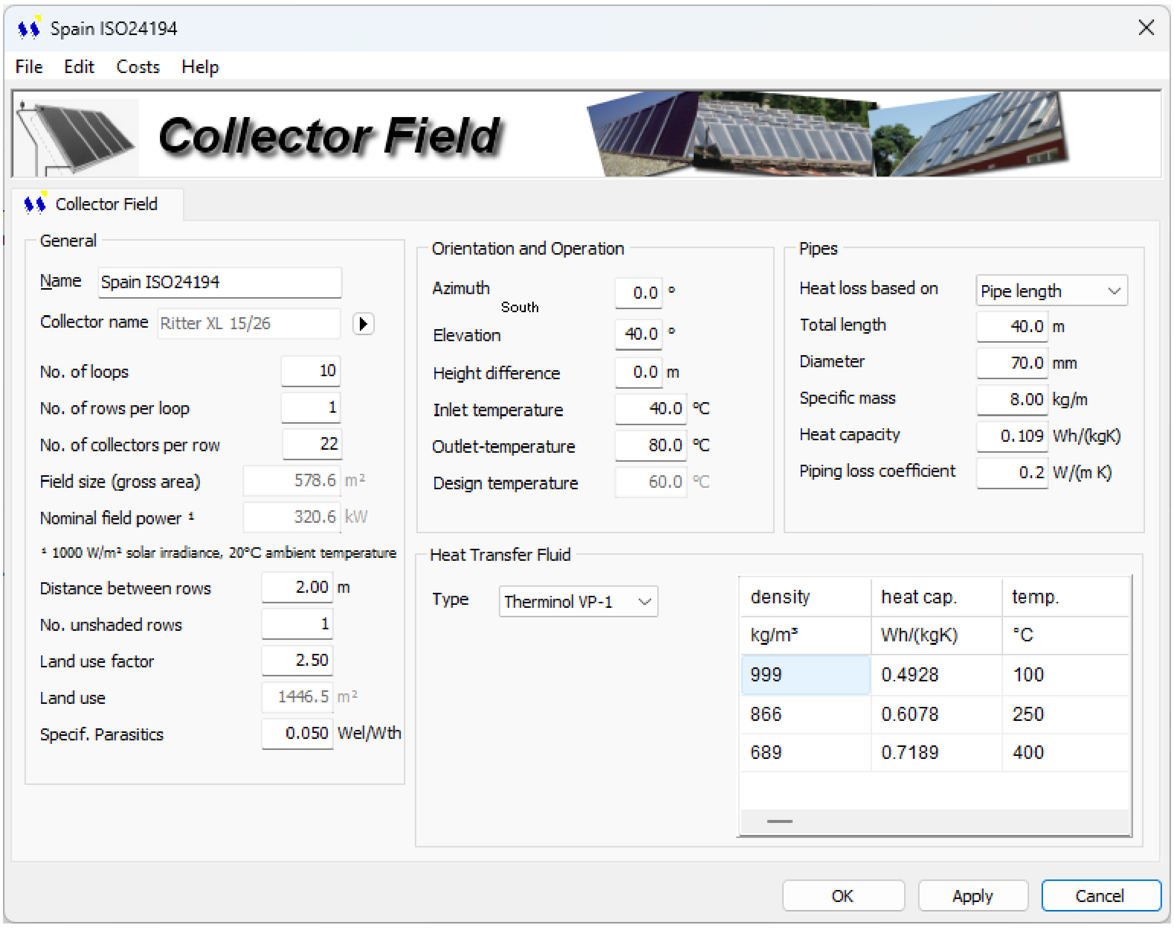
This can be done by using the second tab of the Solar Collector window.

After pushing the button *Load SolarKeymark Database*, users may search for a collector supplier and chose the collector name. The complete dataset of the selected collector is copied to the "Solar Collector" tab and may be used for the next simulation once the *OK* or the *Apply* button is pushed.
If this collector shall be used for further simulations in the future, the dataset should be stored as "*.gpa" file using the *File|Save* Menu. Don't forget to rename the Collector *.gpa to avoid overwriting of the one which has been loaded originally.



ISO 24194 Collector Field

This input form defines the collector field specific parameters:



General Parameters:

- *Collector field name*
- *Collector name (will be copied automatically from the solar collector mask)*
  Pressing the triangle button behind the name directly starts the solar collector input mask
- *Total number of loops*
- *Number of rows per loop*
- *Number of collectors per row*
- *Field size (aperture area)* $A_{aperture}$
  will be calculated automatically from the no. of loops * no. of rows per loop * no. of collectors per row * collector aperture area
- *Nominal field power*
  Field power with chosen collector at reference irradiance, design temperature, ambient temperature of 20°C and zero incidence angle
- *Distance between rows:* Distance between the end of one collector and the beginning of the next, projected on the horizontal plane (i.e., not on the ground if the collectors are

tilted)

- *Number of unshaded rows:* For most plants the southernmost row is unshaded, so the default value should be one, but there might be a kind of opaque fence or wall around the solar field and than this number should be zero.
- *Land use factor:* required land are per m^2 of collector area. Includes area for fences, roads etc.
- *Land use:* total land required for the plant. Calculated from Field size * Land use factor
- *Specific parasitics* in electrical power / thermal output

Orientation and Operation:

- Azimuth (0° = south, 90°=west, -90°=east, 180°=north)
- Elevation (0°=horizontal, 90°=vertical)
- Height difference between a collector and the one behind it. It is used to correct shading. The value is valid only if the height difference is positive, i.e., if the rear collector is positioned higher than the one in front. It is not valid if the following collector is at a lower position.
- Inlet temperature
- Outlet temperature
- Design temperature: calculated as arithmetic mean of inlet and outlet temperature

Pipes

- Piping heat losses can be calculated based on pipe length or base on solar field size for each case the representative piping loss coefficient is required.
- Total length l_{pipe}: sum of hot and cold pipe lengths
- Pipe diameter d_{pipe}
- Specific pipe mass. The table below contains typical values for steel pipes
- Specific heat capacity of the pipe material (carbon steel: 0.136, stainless steel: 0.133, cooper: 0.106)
- Piping loss coefficient, either base on pipe length or on solar field size

Heat Transfer Fluid

- Heat capacity of the heat transfer fluid
- Density of the heat transfer fluid

Seamless steel pipes EN 10220, default wall thickness

outer diameter	s_wall	inner diamter	spec. mass
[mm]	[mm]	[mm]	[kg/m]

10.2	1.6	7.0	0.34
13.5	1.8	9.9	0.52
16.0	1.8	12.4	0.63
17.2	1.8	13.6	0.68
20.0	2.0	16.0	0.89
21.3	2.0	17.3	0.95
25.0	2.0	21.0	1.13
26.9	2.3	22.3	1.4
30.0	2.6	24.8	1.76
31.8	2.6	26.6	1.87
33.7	2.6	28.5	1.99
38.0	2.6	32.8	2.27
42.4	2.6	37.2	2.55
44.5	2.6	39.3	2.69
48.3	2.6	43.1	2.93
51.0	2.6	45.8	3.1
57.0	2.9	51.2	3.87
60.3	2.9	54.5	4.11
63.5	2.9	57.7	4.33
70.0	2.9	64.2	4.8
76.1	2.9	70.3	5.24
82.5	3.2	76.1	6.26
88.9	3.2	82.5	6.76
101.6	3.6	94.4	8.7
108.0	3.6	100.8	9.27
114.3	3.6	107.1	9.83
127.0	4.0	119.0	12.13
133.0	4.0	125.0	12.73
139.7	4.0	131.7	13.39
152.4	4.5	143.4	16.41
159.0	4.5	150.0	17.15
168.3	4.5	159.3	18.18
177.8	5.0	167.8	21.31
193.7	5.4	182.9	25.08
219.1	5.9	207.3	31.02
244.5	6.3	231.9	37.01
273.0	6.3	260.4	41.44
323.9	7.1	309.7	55.47
355.6	8.0	339.6	68.58
406.4	8.8	388.8	86.29
457.0	10.0	437.0	110.24
508.0	11.0	486.0	134.82
559.0	12.5	534.0	168.47
610.0	12.5	585.0	184.19

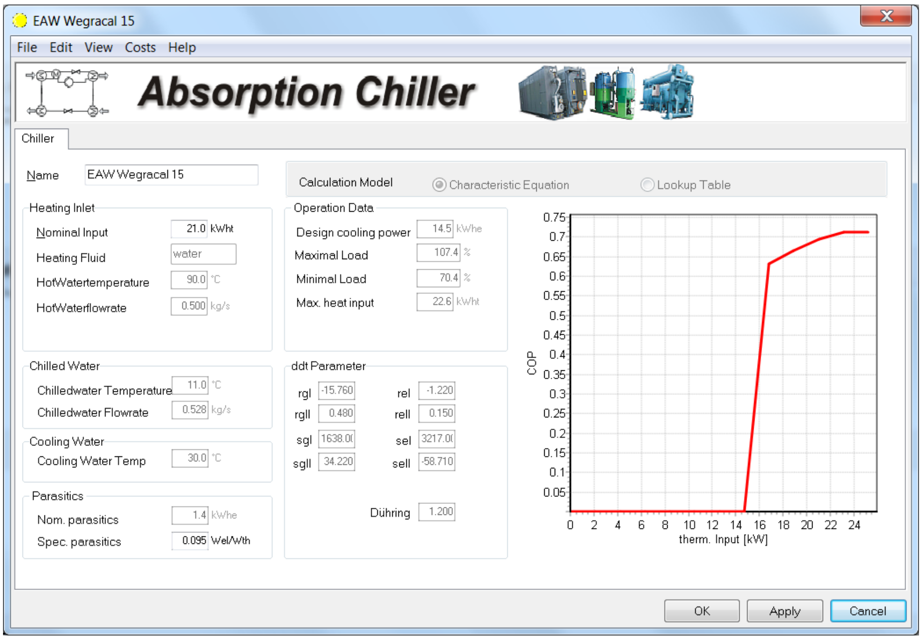
Non-Concentrating Collectors for Chilling

This technology is similar to the Non-Concentrating Collectors for Process Heat technology and uses the same component: Collector Assembly , Collector Field and Thermal Storage. The 1-stage Chiller component is new for this technology.

1-stage Chiller

A model for the 1-stage, steam driven chiller is available for usage together with Non-Concentrating Collector Field as heat source.

The calculation of a hot water heated one stage chiller is realised with the characteristic equation model. The operation window is similar to the one for the two stage chiller, except the specific parameters (*ddt Parameter*) for the characteristic equation and the added information of the hot water flow rate. The nominal parasitics are calculated for the design cooling power and the specific parasitics.



The characteristic equation uses the three external arithmetic mean temperatures to calculate the cooling power and the COP. The model is independent from the mass flow rates. In this application of the model, the inlet cooling water temperature and the outlet chilled water temperature is fixed. With a given hot water temperature and a given solar thermal power it calculates the available cooling power.

The used parameters were published for the TRNSYS type177 by Albers [Alb08]. They are only valid in a specific temperature range for the incoming heating fluid temperature. In case the incoming temperature is greater than the maximum limit, the temperature for the calculation is set to the maximum value. If the incoming temperature goes below the minimum limit, the machine does not work and the cooling power is set to zero.

The solar field does not deliver a constant mass flow rate. Thus a virtual three way mixer valve is used, to ensure a constant mass flow into the chiller. Subsequently the model implementation of this three way valve is explained.

With a given incoming temperature the model calculates a needed heating power. If the given solar thermal power is not sufficient to cover the demand, the incoming temperature is lowered by the mixer valve till the needed heating power meets the solar thermal power. If the delivered solar thermal power is not sufficient to reach the minimum inlet temperature, with a given constant mass flow, the cooling power will be also set to zero.

The chiller model is based on the Dühring's rule for the dissolution field of aqueous lithium bromide:

$$(T_G - T_A) = (T_C - T_E) \cdot B$$

T_X : internal arithmetic mean temperature at the

G : Generator,

A : Absorber,

C : Condenser,

E : Evaporator.

B : Dühring coefficient (for single-effect H_2O/LiBr absorption chiller B is 1.1)

With the equations for the heat transfer:

$$\dot{Q} = \Delta T \cdot U$$

$$U = kA$$

and the enthalpy balance:

$$\dot{Q} = \sum \dot{m}h$$

and the assumption of adiabatic heat exchangers, the internal temperatures (T_X) can be replaced by the external temperatures (t_x), leading to the characteristic temperature difference:

$$\Delta\Delta t = (t_G - t_A) - (t_C - t_E) \cdot B$$

with the combined heat flux of absorber and condenser:

$$\Delta\Delta t = t_G - (1 + B) \cdot t_{AC} + B \cdot t_E$$

$$\dot{Q}_E = s_E(\Delta tac) \cdot \Delta\Delta t - s_E(\Delta tac) \cdot \Delta\Delta tmin_E(\Delta tac)$$

with

$$s_E(\Delta tac) = s_{EI} + s_{EII} \cdot \Delta t_{ACE}$$

$$\Delta\Delta tmin_E(\Delta tac) = r_{EI} + r_{EII} \cdot \Delta t_{ACE}$$

$$\Delta tac = t_{AC} - t_R$$

The values of s_{EI}, s_{EII}, r_{EI} and r_{EII} are taken from the published parameters for the TRNSYS TYPE 177 [Alb08] but they can also be found by a minimum of four reference operation points [Alb02]. The model accuracy might be enhanced by applying a multiple linear regression with more operation points to find the model parameters [Wit08].

The same procedure is done for the generator:

$$\dot{Q}_G = s_G(\Delta tac) \cdot \Delta\Delta t - s_G(\Delta tac) \cdot \Delta\Delta tmin_G(\Delta tac)$$

The rejected heat at the absorber and condenser is finally calculated, using the energy balance:

$$\dot{Q}_{AC} = -(\dot{Q}_G + \dot{Q}_{AC})$$

The given specific parasitic value includes approximate consumption of the external pumps and the cooling tower. If another cooling technology is used, the value can be modified in the field specific parasitics.

The maximal and minimal load value is fixed by the upper and lower limit of the hot water inlet temperature.

Grid Connected PV System

Since version 3.0 **greenius** is able to model concentrating PV systems. The choice is done in the Select Technology window. The required input for Photovoltaic systems component (non-concentrating) and Concentrated PV component are very similar. Concentrating PV systems include an additional component for the Concentrator and the PV module form contains additional data, which is not visible if non-concentrating PV was chosen.

For the calculation of grid-connected PV systems the following components exist:

- Photovoltaic module
- Inverter
- Grid-connected PV system

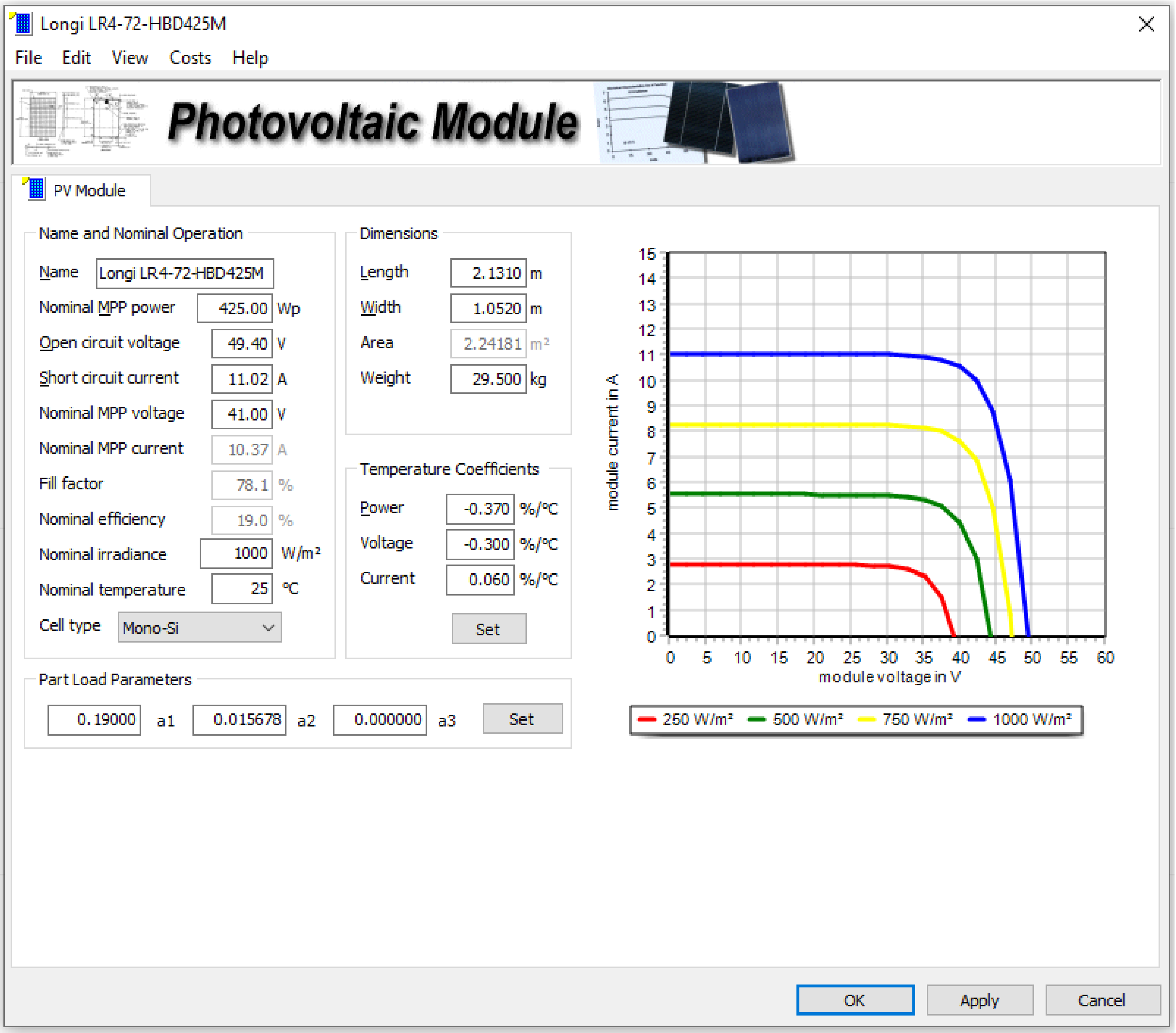
PV Module

The technical parameters of a single photovoltaic module are shown on this form. A relative small set of parameters is sufficient so that **greenius** can calculate and display the most important module characteristics.

The menu entry *Costs* opens the module costs input window. The specific costs are multiplied by the peak power of the modules. The costs of the PV system result from the sum of the costs of the modules and the costs of the inverter. The land use is calculated in the PV system window.

At the menu entry *View* the user can choose between the following diagrams:

- Efficiency over irradiance at different temperatures
- Power over irradiance at different temperatures
- Current over voltage at different irradiances
- Power over voltage at different irradiances
- Current over voltage at different temperatures
- Power over voltage at different temperatures



Part Load Parameters

For simulations in **greenius** the characteristics of the efficiency over the irradiance are mostly relevant. For good simulation results it is essential that the part load parameters have been chosen carefully. If no part load parameters are known, **greenius** can estimate typical part load parameters depending on the cell type. Therefore, the button *Set* or the menu entry *Edit|Set Typical Part Load* must be clicked. This button is disabled for concentrating PV systems.

The efficiency versus the irradiation is calculated using the formula given below:

$$\eta(E,T_0) = a_1 + a_2 \ln\left(\frac{E}{E_0}\right) + a_3\left(\frac{E}{E_0} - 1\right)$$

with

E_0 nominal irradiation = 1000 W/m²

E current irradiation in W/m²

T_0 nominal temperature = 25°C

Since it is possible to change the part load parameters independently from those parameters defining the nominal efficiency (module area, nominal MPP power, nominal irradiance), a parallel offset is applied to the efficiency curve if necessary by adjusting the parameter a1, in order ensure that the curve meets the nominal efficiency.

The graphs on the right hand side are not for nominal conditions but they include losses caused by increased module temperatures and non-uniform irradiation.

Temperature Coefficients

Three temperature coefficients for the following parameters can be defined:

- Power
- Voltage
- Current

These three coefficients refer to the maximum power point, and **NOT** to the open circuit voltage or short circuit current. However, only the temperature coefficient for the power is relevant for the calculation of the module's electricity output. Therefore, it is no big problem that the temperature dependency of voltage and current in the MPP are often missing in the data sheets. Those two values are for information only. In the data sheets for PV modules delivered with **greenius** they are set to zero if not published.

The estimation of typical parameters based on the chose *cell type* is also possible for the temperature coefficients.

Additional input data for concentrating PV modules:

These modules are usually requiring an active cooling since the concentrated sunlight could cause high temperatures and cell damage. The needed cooling power may be calculated from the module efficiency and the solar input to the module. In order to account for this cooling power, **greenius** needs additional input data. There are two different modes of operation:

1. Preset of a constant module temperature
2. Preset of a constant thermal transmission coefficient.

The operating temperature of the modules has an impact on the efficiency and therefore also on the required cooling power. Thus defining a constant thermal transmission coefficient requires an iterative calculation of the module temperature.

Specific parasitics are an additional input parameter for concentrating photovoltaic modules in **greenius.** They must be given as kW electrical power per kW thermal cooling power.

For concentrating PV systems the power temperature coefficient is of special significance since these cells show normally operating temperatures which are considerably above 25°C. Here the relative change of the nominal MPP-Power (or the nominal efficiency) based on the nominal value has to be given.

PV Inverter

This component represents a DC/AC inverter used with both technologies, concentrating and non-concentrating PV.

The first group of parameters in the component form allows the definition of relevant voltage, current and power values:

- Nominal and maximum DC power

- Minimum and maximum DC voltage
- Maximum DC current

The nominal AC power is calculated based on the nominal DC power and the nominal efficiency.

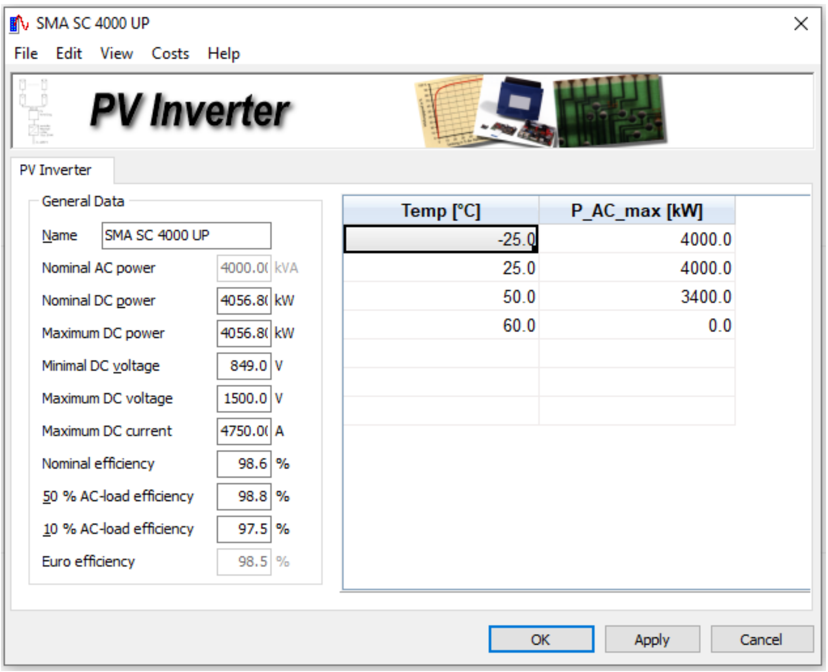
The maximum DC power parameter represents the maximum DC power that the inverter supports, not the maximum DC power generated by the PV modules.

The following parameters define the efficiency and part load behaviour of the inverter. With the part load efficiency at 10 % and 50 % load and the nominal efficiency the efficiency characteristic is calculated and shown on a chart. Furthermore, the Euro efficiency is calculated and shown.

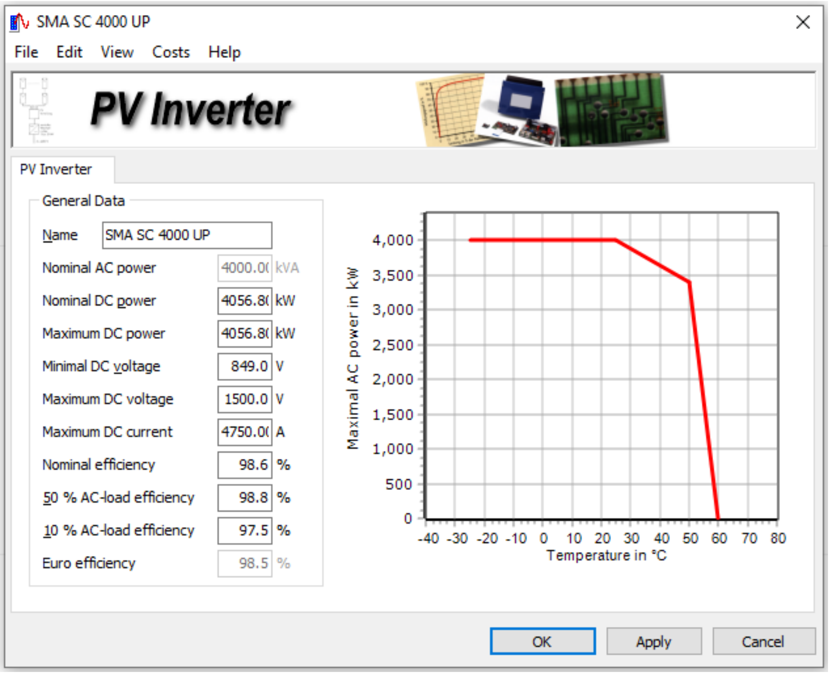
At the menu entry *View* the user can choose between the following diagrams:

- AC power-temperature graph
- AC power-temperature table
- Efficiency graph

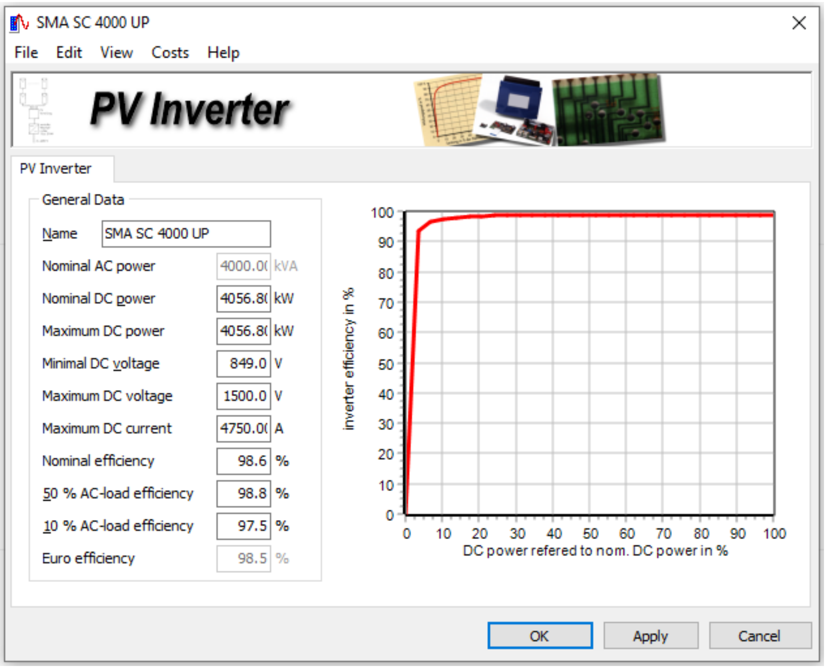
The performance of the inverter depends on the ambient temperature. The AC power-temperature table defines the maximum AC power for each temperature range. The temperatures entered in the table must always be increasing. The maximum AC power is used to calculate clipping when the AC power input exceeds this value.



AC power-temperature table



AC power-temperature graph



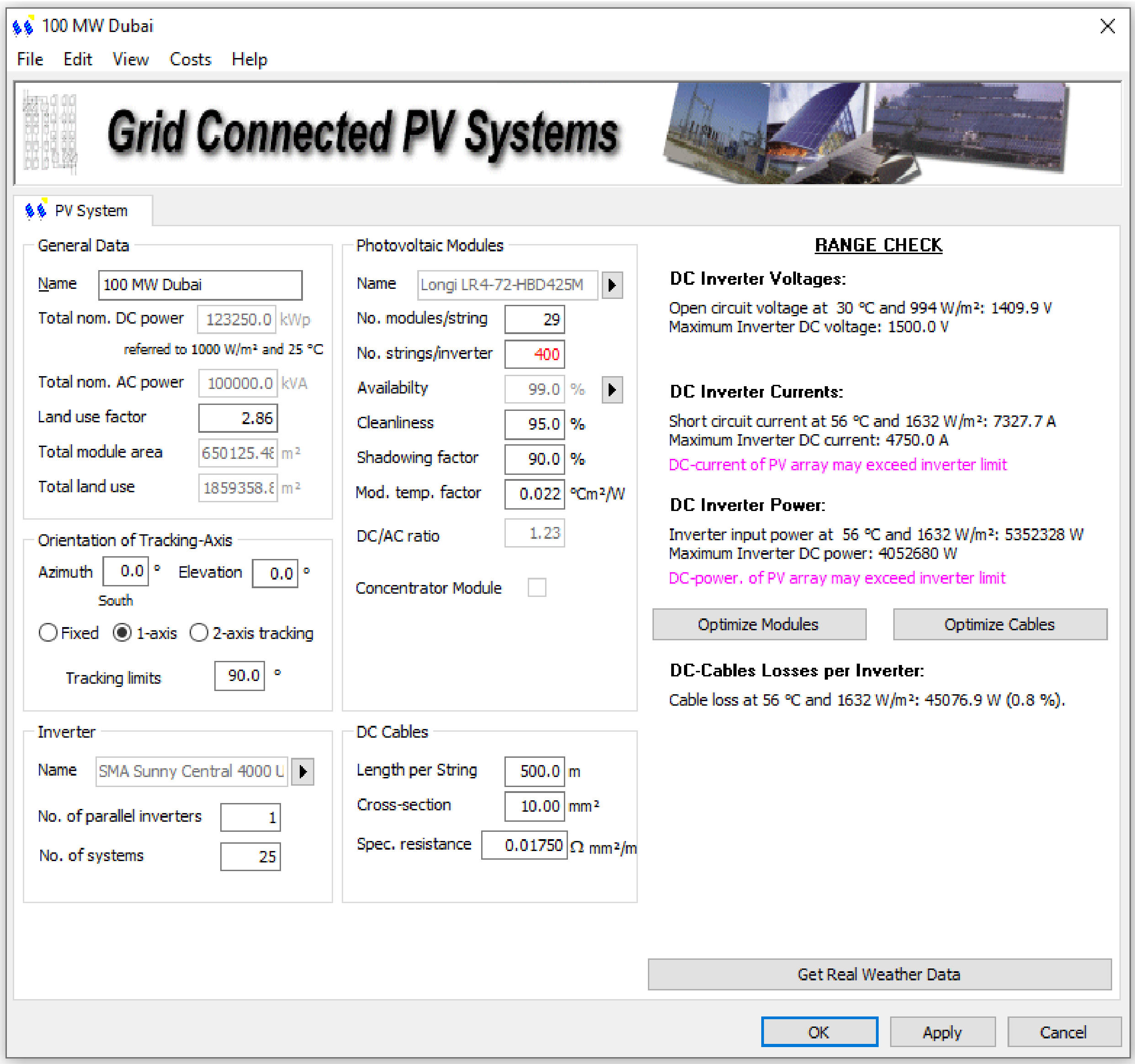
Efficiency graph

The menu entry ■*Costs* opens the inverter costs input window. The specific costs are multiplied by the nominal AC power of the inverter. The costs of the PV system result from the sum of the costs of the modules and the costs of the inverter. The land use of the inverters is not considered.

Grid Connected PV System

The overall PV system is defined here. The form gives an overview of the whole system performance and offers several charts and tools to optimise the configuration of the system.

The menu entry *Costs* opens the [PV system costs window](). The total costs result from the sum of the costs of the inverter and the costs of the modules, whose specific costs are entered in their respective costs input window. The specific costs of the PV system result from the division of the total costs of the system by the total nominal AC power of the system.



General Data

The general data group allows definition of a name and shows the total DC and AC power at peak conditions (1000W/m² and 25°C) as well as the total module area.

The parameter *Land Use* is only important for economic calculations. It is the result of multiplying the total module area by the land use factor. The land use of the inverters is not considered in the calculation.

The *degradation* parameter is a simple way to account for performance losses of the PV system over life time without simulating each single year of operation. Instead the electricity output in year i of operation is calculated using

$$Q_i = Q_{TOY} \cdot \left(1 - x_{degradation}\right)^i$$

where $x_{degradation}$ is the user defined degradation parameter in the form and Q_{TOY} the electricity of the simulated typical operation year.

Orientation and Tracking

This group allows definition of the module orientation and the tracking technology (fixed, 1-axis, 2-axis).

The meaning of input parameters depends on the system type:

Fixed system:

- Azimuth: direction of the projection of the module surface normal vector into the horizontal plane. (south = 0°, clockwise positive)
- Elevation: tilt angle of the module against the horizontal plane (0°: horizontal, 90°: vertical)

Single axis tracking system:

- Azimuth angle of the tracking axis. (south = 0°, clockwise positive)
- Elevation: tilt angle of the tracking axis against the horizontal plane (0°: horizontal, negative: positive:)
- Tracking limits: to be used when the tracking mechanism has only a limited operation angle. The angle is defined defined from zenith = 0°.
  (±90°: means full tracking from left to right horizon without restrictions, ±60°: means limited angle left and right from the zenith)

For two-axis tracking system the collector surface normal is always oriented toward the sun.

For concentrated PV, only 2-axis tracking is possible since both other options do not make sense in combination with a concentrator.

Inverter

The chosen inverter component name is shown here. Clicking the triangle button next to the name opens the inverter component form. The number of parallel inverters per system as well as the number of systems can be set.

Photovoltaic Modules

The name of the chosen PV module is shown. Clicking the triangle button shows the PV module component form. The number of strings per inverter and PV modules per string can be set. Availability, cleanliness and shadowing are defined here as well. The shadowing factor accounts for the output reduction caused by shadowing between rows. 100 % means no shadowing, 0% means total shadowing.

Module temperature coefficient

The module temperature factor c describes the temperature of the PV module as a function of the irradiation. Higher temperatures of the module cause efficiency reductions compared to the nominal values (see temperature coefficients in the PV module component). The module temperature is shown in the chart when choosing the menu entry *View|Module Temperature*.

The module temperature is determined using

$$t_{Cell} = t_{amb} + c \cdot E_{module}.$$

The following table from [DGS08] can be used to choose the correct value for the temperature coefficient. The default value used in **greenius** is 0.022.

Type of installation	c in °C/(W/m²)
Totally free	0.022
On the roof, large gap	0.028
On the roof, low ventilation	0.032
On the roof, no ventilation	0.043

DC/AC ratio

Ratio of nominal PV array power / inverter nominal DC power.

Sometimes the PV array is designed larger than the inverter. That means the nominal array power (and its nominal current) is higher than the nominal input of the inverter. This is done since it might be an economic solution. The PV array doesn't reach its nominal power very often (or even never, depending on conditions on site) and therefore the inverter might be dimensioned nominally smaller. In case that the actual DC output of the PV array during certain time steps exceeds the maximum DC power of the inverter the excess power is clipped. The expression clipping is used here in contrast to dumping (see Output of PV plants) which occurs when the AC output exceeds the power accepted by the grid (e.g. defined by maximum load for the relevant time step).

DC Cables

The DC cable properties length, cross-section and specific resistance can be set here.

Chart

At the menu entry *View* one of the following options can be chosen:

- Graphic of the system efficiency over the irradiation
- Graphic of the difference between module and ambient temperature over the irradiation
- Tools to check the operating range and to optimise the system
- Tools to define the system using real weather conditions

Range Check

The main feature of this form is the operating range check for the system definition. In this modus, **greenius** calculates automatically voltages, power and currents of the photovoltaic module strings and compares it to the ranges given by the inverter. If there are any problems, **greenius** automatically gives a warning in magenta and marks critical parameters in red. The calculation can however be executed. Most critical is the open circuit voltage defined by the number of modules per string.

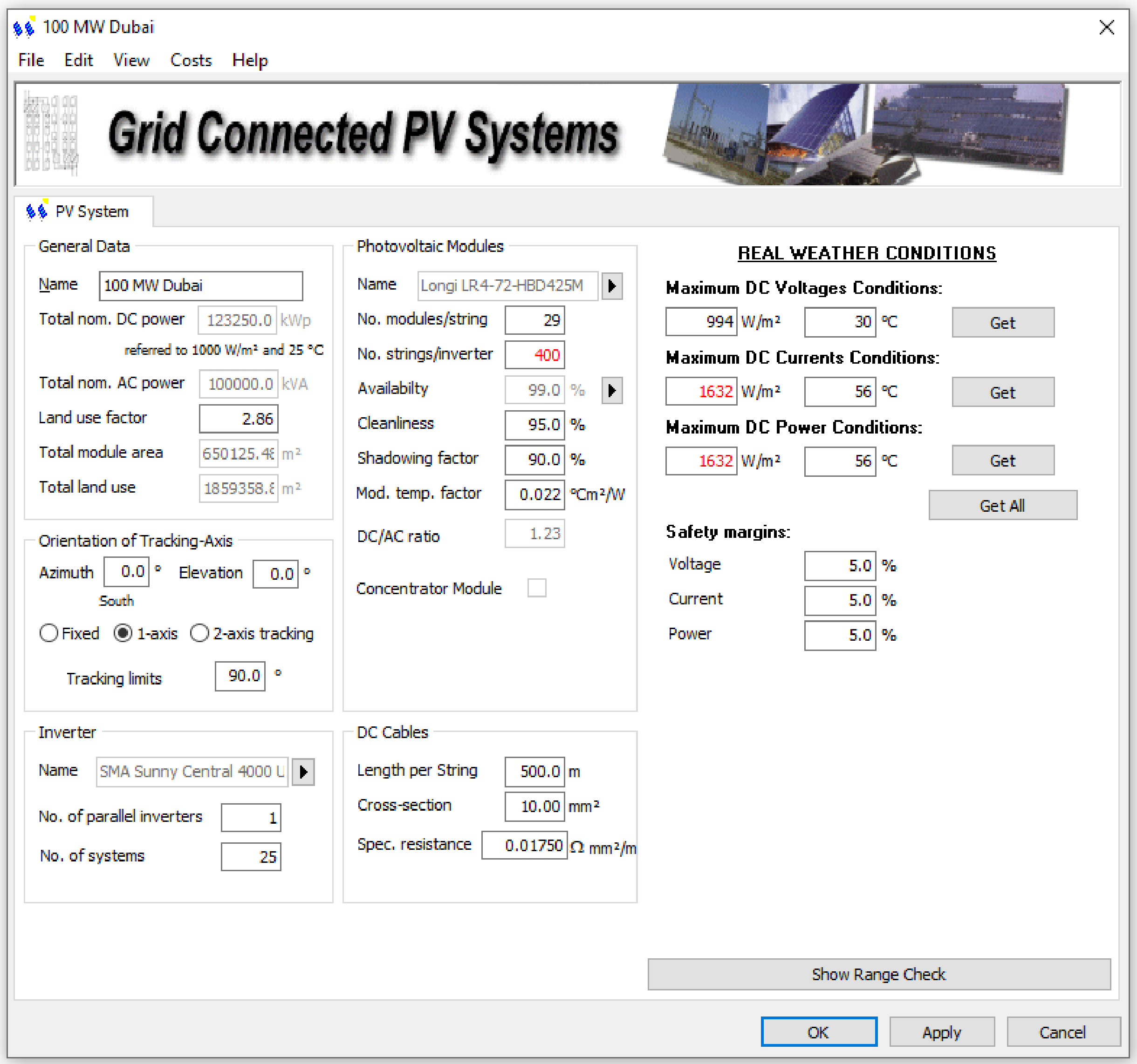
Maximal DC current and DC power may be higher than the values of the inverter for design reasons (see DC/AC ratio).

The button *Optimize Modules* or the menu entry *Edit|Optimize Modules Numbers* estimates the optimum number of modules for the chosen inverter.

The cable cross-sections of the DC lines can be also optimised. The cross section is increased until the DC cable losses are below one percent of the PV module output at nominal conditions. Please note that the DC cable length is defined as average total (from inverter to string + from string to inverter) length per string. In reality, several strings can be joined in parallel and connected to the inverter by one single cable with a bigger cross section. This is not considered in the **greenius** model. The cable losses are calculated on the assumption that each string is connected individually to the inverter with a DC cable with the given parameters for length and cross section.

Real Weather Conditions

By default, the range check is done for an irradiation of 1000 W/m², a minimum module temperature of -10°C and a maximum module temperature of 70°C. The actual values can differ from these values. Therefore, the button *Get Real Weather Data* allows the import of the extreme values of the currently loaded meteo data file. The optimum number of solar modules can deviate from the default case when using local weather conditions. Consequently, the range check should be repeated after loading the real weather data.



The buttons ↳*Get* respectively ↳*Get All* estimates the worst-case weather conditions for all parameters. Allowable voltage, power and current ranges are calculated with the given safety margins .

Concentrating PV Systems

For concentrating PV systems the form shows some special features:

- 2-axis tracking is compulsory
- PV modules are concentrator modules
- The user may choose the power purchase option

The latter option was introduced, since special feed-in tariffs sometimes allow for selling the gross solar electricity production and take the parasitic electricity consumption from the grid. This option may be interesting because the revenues for the solar electricity and the cost for the grid-electricity are different. The buttons ↳*Sell net electricity* respectively ↳*Sell gross electricity* are used to switch between both options.

The number of modules per system for concentrating PV is already fixed from the data given on the concentrator form, since the receiver area is given there. This receiver area, divided by the area of one PV module, gives the total number of PV modules. The number of modules per string and the number of strings per inverter can still be set by the user. Accordingly, the number of inverters is then automatically calculated using

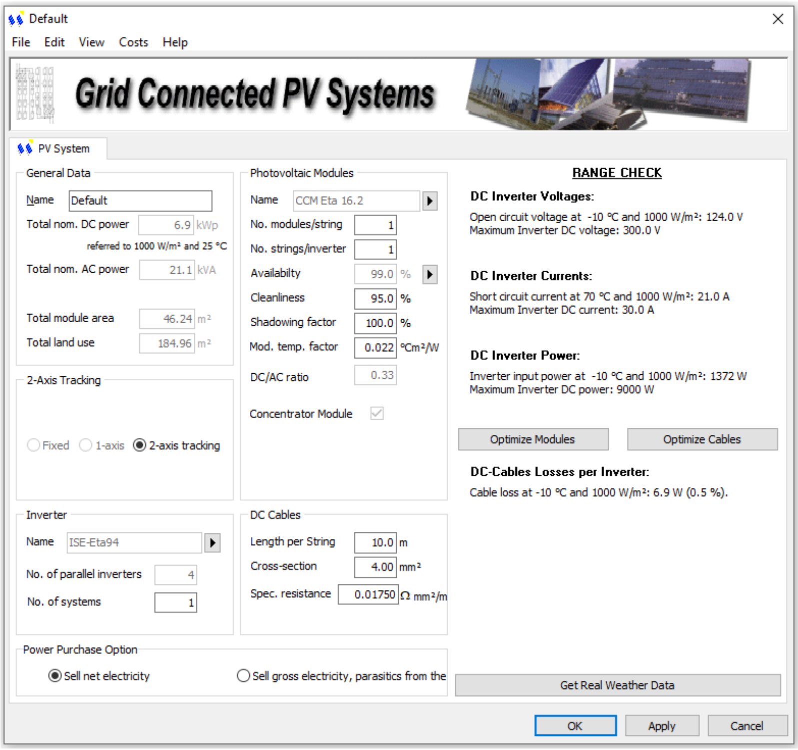
$$n_{Inverter} = \frac{n_{modules}}{n_{strings} \cdot n_{parallel}}$$

n_{moduls} : total number of PV modules (per system)

$n_{strings}$: number of PV modules in series (per string)

$n_{parallel}$: number of parallel strings (per inverter)

Since inverters can only be added as a whole, a warning message is shown, when $n_{strings}$ or $n_{parallel}$ do not yield a whole number for $n_{Inverter}$.

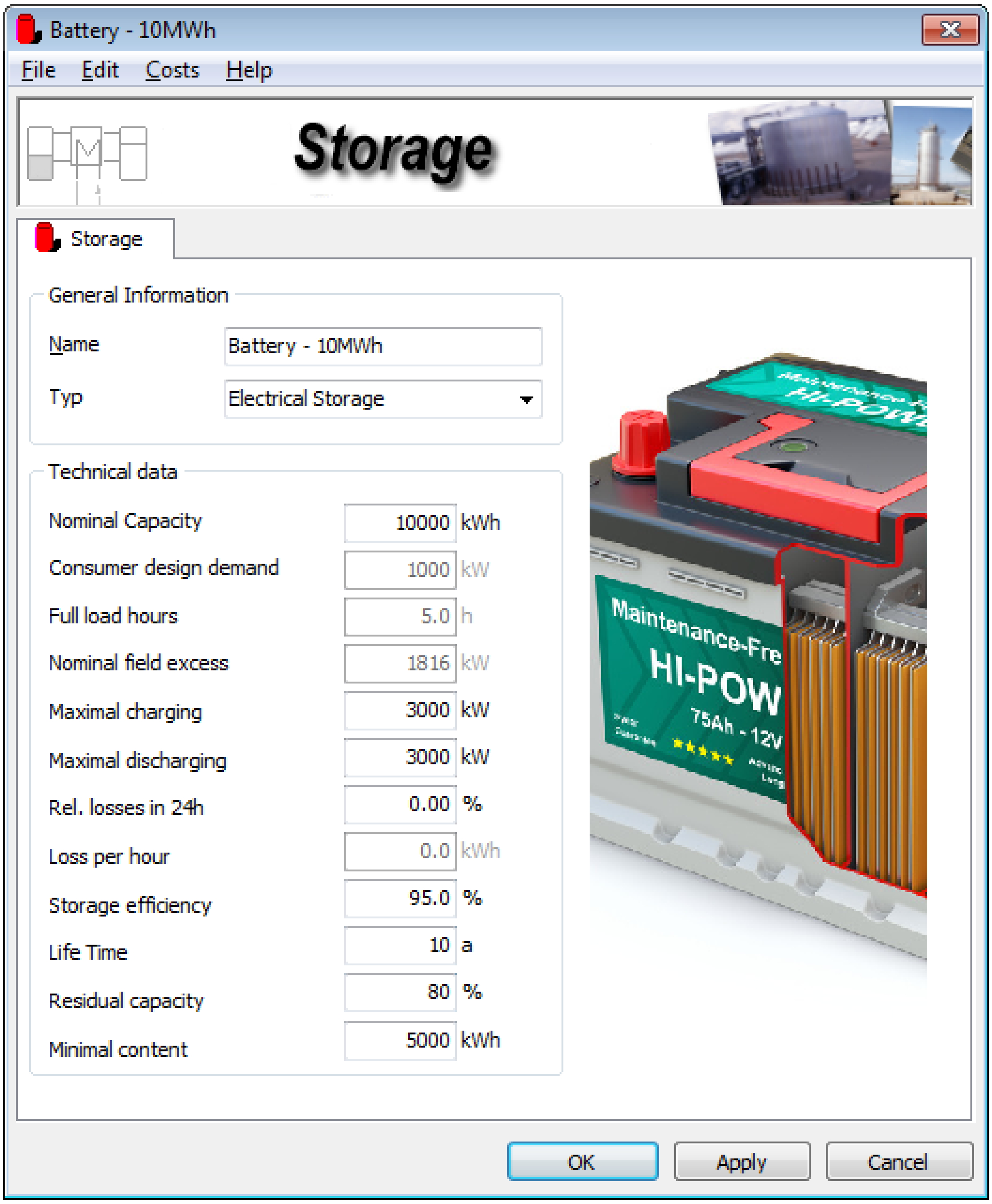


In order to calculate a certain number of identical systems (e.g. for an area of concentrating PV parabolic dishes), the total number of systems may be specified.

Electric Storage (Battery)

As of version 4.4 photovoltaic projects in **greenius** may be equipped with an electricity storage (battery). If you do not want to use a storage in your photovoltaic project set the nominal capacity of the storage to zero or load the component *No Electricity Storage*. The storage model is supposed for low to medium term storage usage. If you use this electricity storage component as seasonal storage (which is possible using the operating strategy component) the storage model may yield misleading results because e.b. storage loss modelling is not exact enough for long periods of time.

The electricity storage component is derived from the thermal storage component and many input parameters are similar. However some additional parameters are required in order to be able to model the battery behaviour. The GPA component files are identical for both storage types, but certain parameters are neglected depending on the storage type.



Input parameters

- The *nominal capacity* gives the nameplate capacity of the electricity storage which is usually not the same as the *usable net capacity* of the storage due to restrictions for the depth of discharge. Depending on the used technology the residual net capacity of the storage is only about 50%.
- The *consumer design demand* is the nominal value defined in the load curve component. It is only used as reference in order to calculate the number of corresponding full load hours.
- The *full load hours* are calculated depending on the *consumer design demand.*
- The *nominal field excess* is calculated as difference between the nominal output of the electricity producing component (e.g. photovoltaic system) and the *consumer design*

demand. It is therefore a measure for the maximum charging power that can be expected.

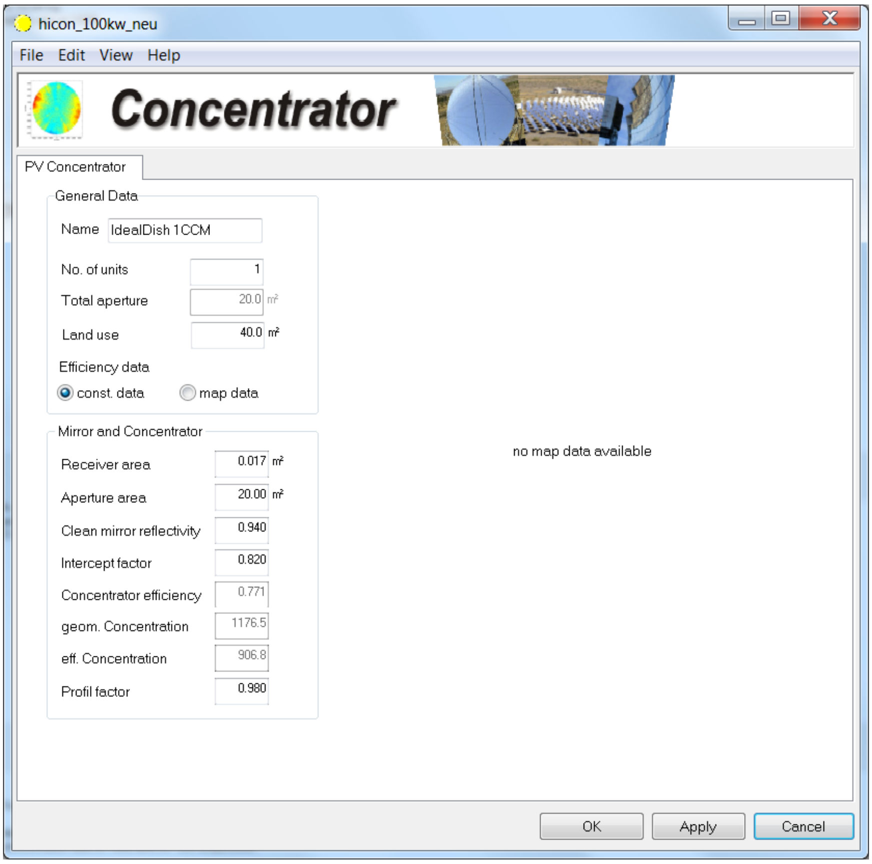
- The *maximal charging* parameter can be used to limit the maximum charging power of the storage. In general, it should be higher than the *nominal field excess*.
- The *maximal discharging* parameter allows the limitation of the discharge power.
- The *relative losses in 24h* can be used to account for losses while the storage is stored in charged state. They are defined in percent per day. Depending on the storage technology those values are usually quite low.
- The *storage efficiency* is used to represent the roundtrip charge/discharge loss of electric energy. While in reality the losses occur during charging as well as discharging, **greenius** accounts all losses when the storage is charged.
- The *life time* of an electric battery is usually smaller than the economic project life time (e.g. 10 compared to 25 years). During the battery's life time it loses capacity which is defined by the parameter *residual capacity* at the end of life time. It is assumed that the capacity reduces linearly from 100% in year 1 to the given residual capacity in the last year of its economic life time. In the following year **greenius** assumes that the battery is exchanged with a brand new one which has 100% again. Please be aware of the fact that the cost related to the battery exchange are not accounted automatically by **greenius**. Instead, you have to define the corresponding costs in the *Additional OM Cost* tabsheet in the cost component.
- The *residual capacity* must be defined at the end of the storage life time defined in the parameter above.
- The *minimal content* is used to define the minimum depth of discharge. Depending on the technology it may be favourable for the storage's life time to not discharge below e.g. 50% state of charge. The net capacity of the storage is the difference between *nominal capacity* defined above and the *minimal content*.

Concentrating PV System

Concentrated PV System is very similar to Grid Connected PV System. In contrast to the name of both technologies, the concentrated PV system is also grid connected, but an additional Concentrator component is included. The other components Photovoltaic Module, PV Inverter and Grid-connected PV System are the same as in the Grid Connected PV System technology. Be aware of the difference between the technology and the component which both are named *Grid Connected PV System*. There are minor differences in the shared components which are described in the corresponding components sections.

PV Concentrator

Here the main parameters of the concentrator for Concentrating PV System are defined. The figure below shows the version of the form for a simple concentrator with constant parameters, which is shown by default. A parabolic dish reflector with 2-axis tracking would be a typical example for a simple concentrator. For this type, the intercept factor as well as the profile factor is independent from the sun position.



Parameters

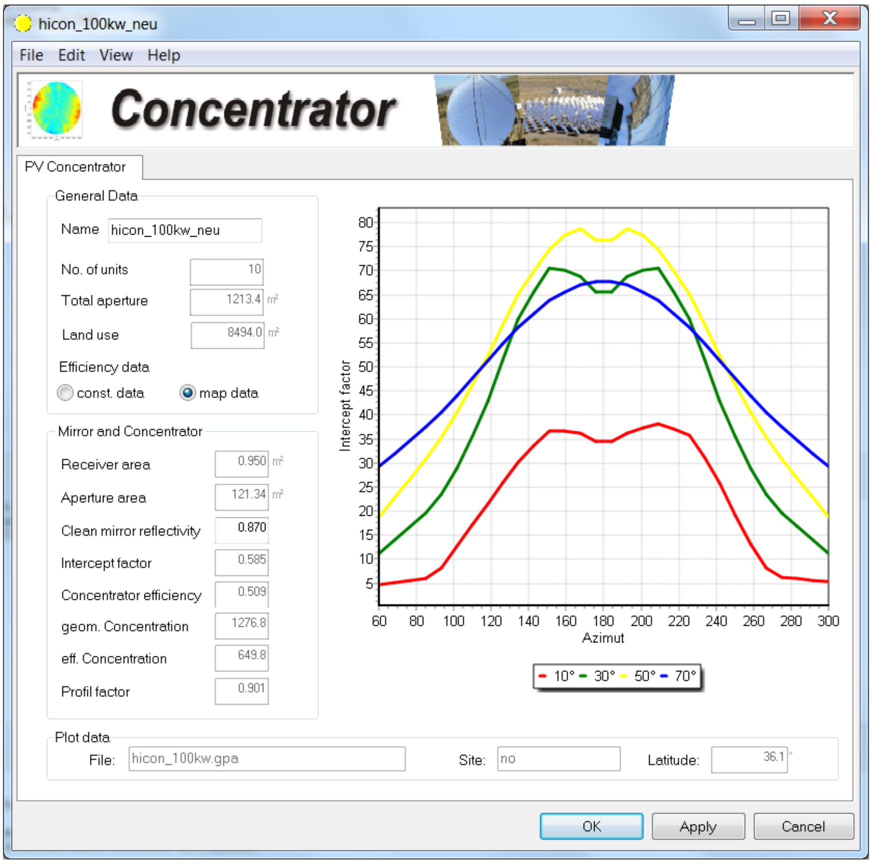
- The *number of units* may be higher than the number of PV modules since more than one concentrator can be used for one PV module. This is common for larger plants using an array of heliostats. In this case the total number must be given here.
- The *total aperture* is calculated from the *number of units * aperture area*.
- The *land use* for concentrating photovoltaic plants is mainly caused by the land use for the concentrators. This parameter must be given on this form but it is used only for the economical calculation.
- By the radio buttons *const. data* or *map data*, the user may decide, which kind of concentrator model is used for the calculation. If const. data is active, the values shown on the left hand side of the form are used for the annual performance calculation. That means, the effective concentration is independent of the sun position. The usage of map data is described below.
- The *receiver area*, together with the area of a single PV module (from Photovoltaic Module) determines the total number of modules.
- The *aperture area* is one of the parameters determining the concentration. This is the entrance area for the solar irradiation, which is commonly smaller than the mirror area, since the mirrors are curved.
- The *mirror reflectivity* accounts for the imperfect reflection of the sun beams.
- The *intercept factor* accounts for the difference between the area of the focal spot and the receiver area. Normally the focal spot in the receiver plane is larger than the receiver area and this causes losses of concentrated irradiation. For larger plants with heliostat

arrays as concentrators, this parameter combines all efficiencies up to the surface of the photovoltaic cell, including cosine losses and the losses of an optional secondary concentrator.

- The *concentrator efficiency* is calculated from *intercept factor* * *mirror reflectivity*.
- The *geometrical concentration* is calculated from the mirror area divided by the receiver area. It does not include the concentrator efficiency.
- The *effective concentration* in contrast considers this efficiency it is calculated from *geometrical concentration* * *concentrator efficiency*.
- The *profile factor* is a parameter which accounts for the efficiency decrease due to non-uniform irradiation of the photovoltaic module.

Map Data

If the radio button map data is activated, the effective concentration and the profile factor are taken from performance maps, stored in a file and generated by external simulation tools (e.g. HFLCAL, developed by DLR). The general layout of this file is explained below. If the radio button map data is active, some of the input values on the left hand side are no longer available because they are taken from the file and they are shown in the graph. The mirror reflectivity is the only input which may be modified by the user in this case.



The name of the file, containing the data, is shown as well as the site and the latitude for which the performance maps are valid. The site name is given here only for informational purposes to ease the allocation of the file and a site. Since the concentrator performance map is given for azimuth a sun height angle, it is valid for all sites with the same latitude. If the latitude differs more than 1° from the latitude of the chosen site (in the site form), a warning message is displayed and the user is asked to make a correction.

Using the menu entry ▀View, it is possible to switch between the following diagrams:

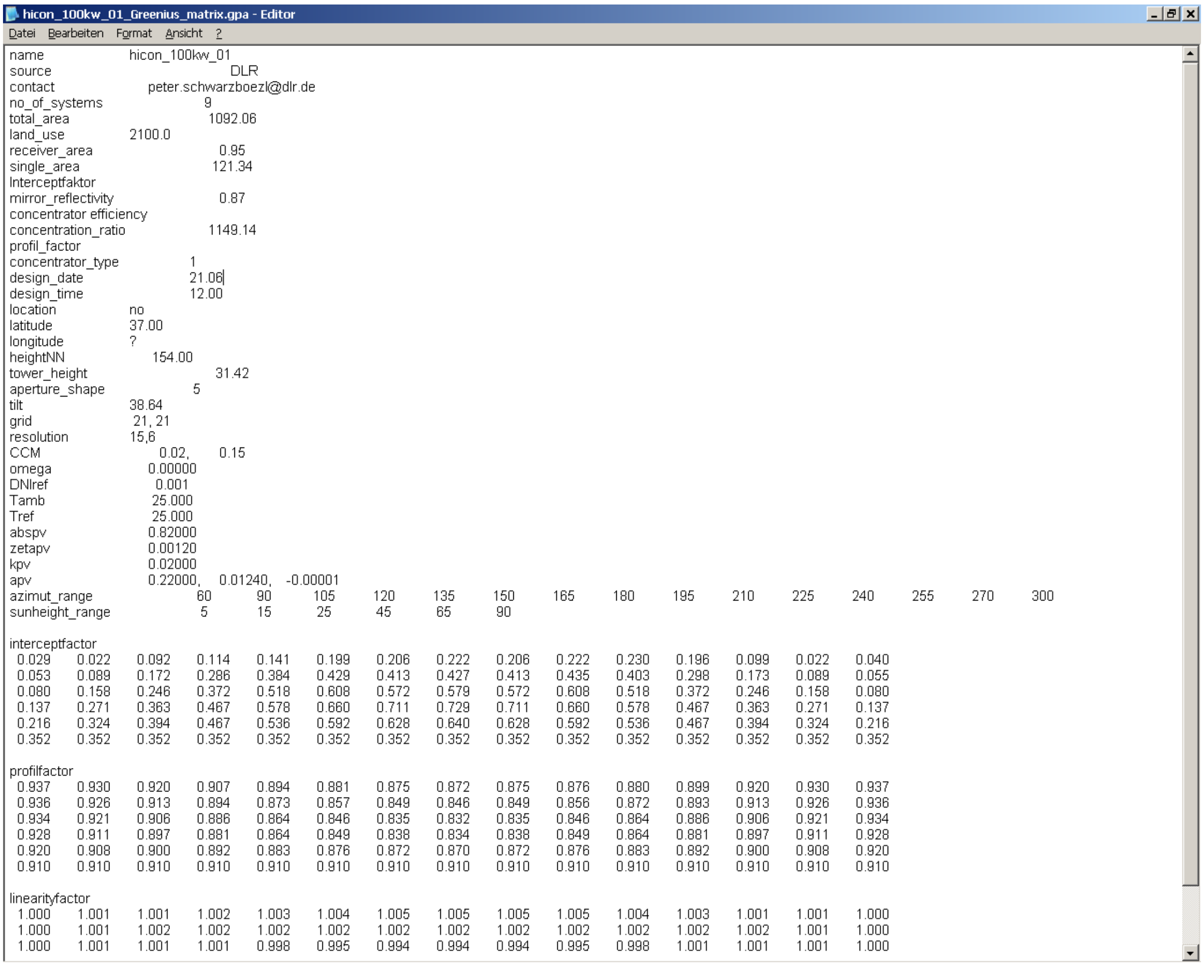
- concentrator efficiency vs. azimuth angle
- profile factor vs. azimuth angle
- linearity vs. azimuth angle

Parameter for all three diagrams is the sun height angle.

Format of the concentrator input file

This file is very similar to the input file for the power block for parabolic trough plants. It contains a number of single parameters, which are defining the design values, followed by information for the performance maps. Some of this information is not used by **greenius**, but may be used to identify and eventually recover the data.

The *azimut_range* and the *sunheight_range* contain supporting points of the the 2-dimensional performance maps, followed by the map data for intercept factor, profile factor. The number of values per line is equal to the number of supporting points for azimut_range and the number of lines is equal to the number of supporting points for sunheight_range. The azimuth_range and sunheight_range data must be given in ascending order.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Datei Bearbeiten Format Ansicht ?

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longitude           ?
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DNIref                 0.001
Tamb                  25.000
Tref                  25.000
abspv                 0.82000
zetapv                0.00120
kpv                   0.02000
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azimut_range                 60      90      105     120     135     150     165     180     195     210     225     240     255     270     300
sunheight_range              5       15      25      45      65      90

interceptfactor
 0.029   0.022   0.092   0.114   0.141   0.199   0.206   0.222   0.206   0.222   0.230   0.196   0.099   0.022   0.040
 0.053   0.089   0.172   0.286   0.384   0.429   0.413   0.427   0.413   0.435   0.403   0.298   0.173   0.089   0.055
 0.080   0.158   0.246   0.372   0.518   0.608   0.572   0.579   0.572   0.608   0.518   0.372   0.246   0.158   0.080
 0.137   0.271   0.363   0.467   0.578   0.660   0.711   0.729   0.711   0.660   0.578   0.467   0.363   0.271   0.137
 0.216   0.324   0.394   0.467   0.536   0.592   0.628   0.640   0.628   0.592   0.536   0.467   0.394   0.324   0.216
 0.352   0.352   0.352   0.352   0.352   0.352   0.352   0.352   0.352   0.352   0.352   0.352   0.352   0.352   0.352

profilfactor
 0.937   0.930   0.920   0.907   0.894   0.881   0.875   0.872   0.875   0.876   0.880   0.899   0.920   0.930   0.937
 0.936   0.926   0.913   0.894   0.873   0.857   0.849   0.846   0.849   0.856   0.872   0.893   0.913   0.926   0.936
 0.934   0.921   0.906   0.886   0.864   0.846   0.835   0.832   0.835   0.846   0.864   0.886   0.906   0.921   0.934
 0.928   0.911   0.897   0.881   0.864   0.849   0.838   0.834   0.838   0.849   0.864   0.881   0.897   0.911   0.928
 0.920   0.908   0.900   0.892   0.883   0.876   0.872   0.870   0.872   0.876   0.883   0.892   0.900   0.908   0.920
 0.910   0.910   0.910   0.910   0.910   0.910   0.910   0.910   0.910   0.910   0.910   0.910   0.910   0.910   0.910

linearityfactor
 1.000   1.001   1.001   1.002   1.003   1.004   1.005   1.005   1.005   1.005   1.004   1.003   1.001   1.001   1.000
 1.000   1.001   1.002   1.002   1.002   1.002   1.002   1.002   1.002   1.002   1.002   1.002   1.002   1.001   1.000
 1.000   1.001   1.001   1.001   0.998   0.995   0.994   0.994   0.994   0.995   0.998   1.001   1.001   1.001   1.000
```

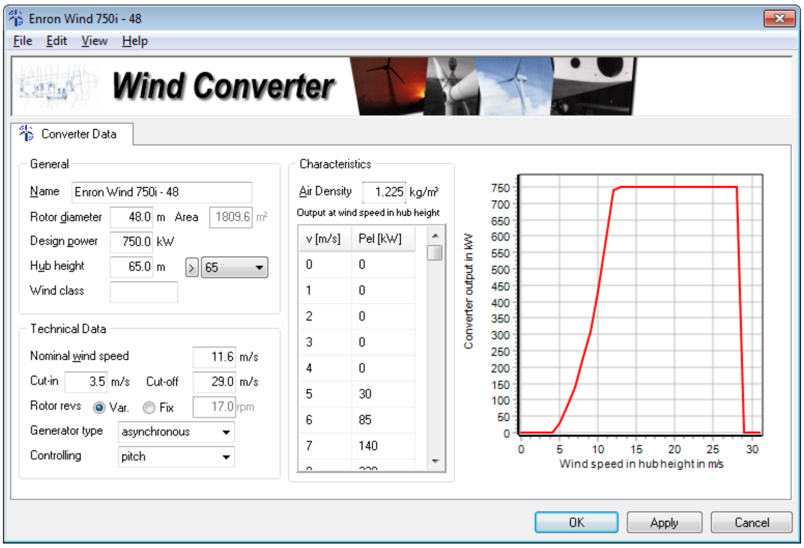
Wind Power

Wind parks can be calculated using the technology *wind power*. The following [components](#) exist

- [Wind Converter](#)
- [Wind Park](#)

Wind Converter

The technical parameters of wind converters can be defined here. The wind converter output power depending on the wind speed in hub height is defined here in a table. The simulation interpolates between the given points linearly. The power curve can be also displayed graphically. This graphic can be saved, copied or printed with a right mouse click. At the menu entry *View|Power Coefficient* the power coefficient can be calculated and shown as graphic.



At the menu entry *Edit|Hub Height|add* or the button >> the present hub height can be added to the selection list. The menu entry *Edit|Hub Height|delete* deletes values from the selection list. The chosen hub height is significant for the calculations since the wind velocity increases with hub height.

Most suppliers offer large wind turbines with more than 1.5 MW. **greenius** contains a couple of datasets for smaller wind turbines for historical reasons. Not all suppliers disclose the required datasets, therefore we can only provide data for wind turbines were the relevant data is published. Users may edit the datasets and create additional ones for there own purposes.

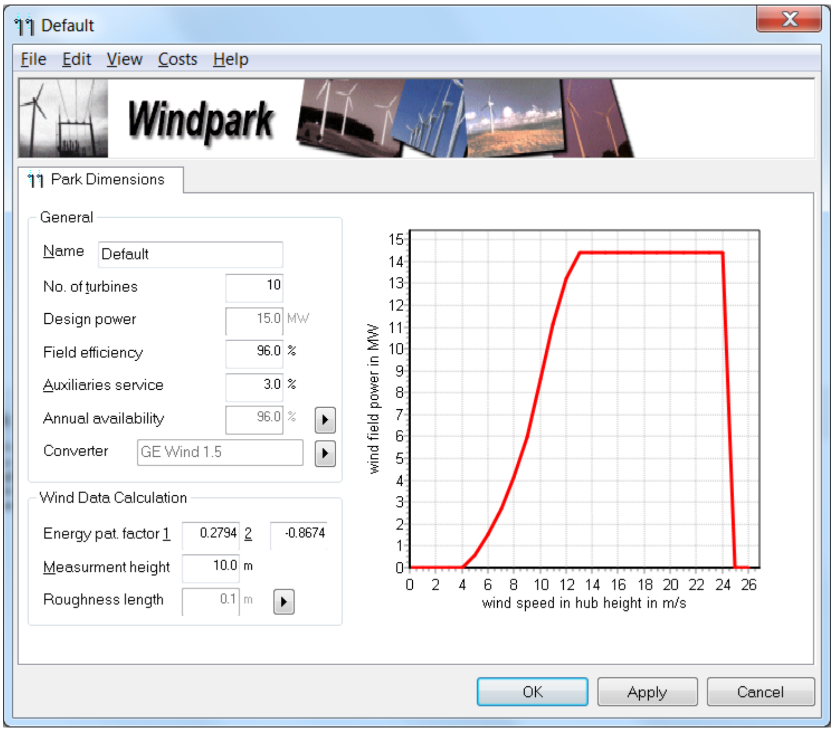
Current wind turbines are made for a certain wind class according to IEC. This classification considers different average wind velocities and turbulence intensities at hub height. Turbulence intensity quantifies how much the wind varies typically within 10 minutes. Turbines made for lower wind velocities (higher wind class) have typically longer blades and taller towers compared to those made for higher wind velocities. Class A types are made for higher turbulence intensity and thus more robust than class B types.

Class	IA	IB	IIA	IIB	IIIA	IIIB	IVA	IVB
Average Wind Speed (m/s) at hub height	10	10	8.5	8.5	7.5	7.5	6	6
Turbulence	18%	16%	18%	16%	18%	16%	18%	16%

Wind Park

The technical parameters of wind parks are defined here. The number of wind converters, field efficiency, Availability, and wind speed parameters are important.

For the simulations the average hourly wind speed must be converted from the measurement height to the hub height. A very critical parameter therefore is the roughness length that is defined at the location (see 4.5.2). At the menu entry *View|Wind Speed over Height* a graphic shows the increase of the wind speed with the height.



For the simulations the mean hourly values of the wind speed from the meteorological data set is used. Since the power of wind turbines depends not linearly on the wind speed this underestimates the power output systematically. The energy pattern factor k_E tries to compensate this. It is defined as follows:

$$k_E = \frac{\frac{1}{n}\sum_{i=1}^{n} {v_i}^3}{\left(\frac{1}{n}\sum_{i=1}^{n} v_i\right)^3} = \frac{\frac{1}{n}\sum_{i=1}^{n} {v_i}^3}{\bar{v}^3} \geq 1$$

greenius uses the following empirical function for the energy pattern factor:

$$k_E = 1 + f_1 \cdot v^{f_2}$$

The parameters *f1* and *f2* can be defined. Without any further information it is strongly recommended to do not change these parameters. At higher wind speeds the wind speed keeps more constant so that only slight variations from the mean value can be expected. If f_1 is set to zero, the energy pattern factor has no influence.

At the menu entry *View|Energy Pattern Factor* the energy pattern factor depending on the wind speed is shown graphically.

The menu entry *Costs* opens the Wind costs input window.

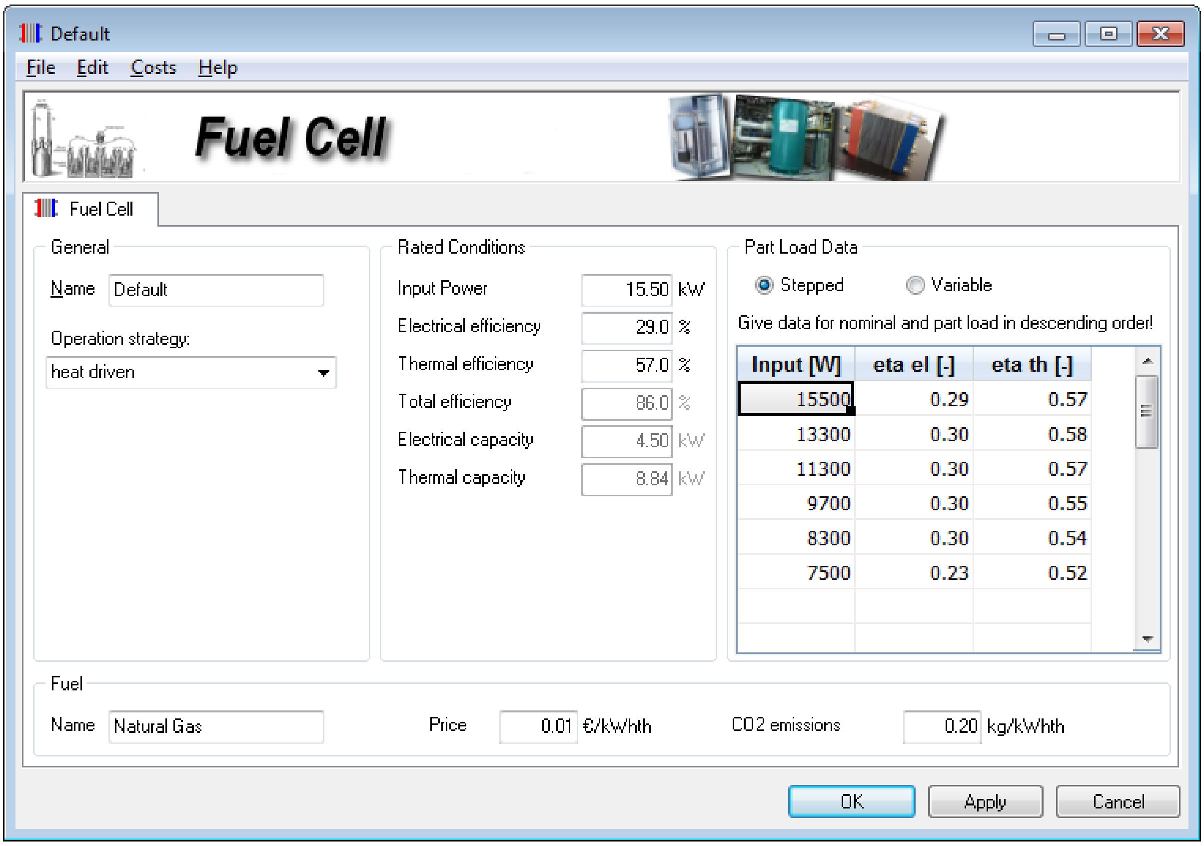
Fuel Cells

Fuel Cells can be calculated using this technology. It relies on one single technical component:

- Fuel Cell

Fuel Cell

This component represents a simple, efficiency based model of a fuel cell. The available input parameters are described below.



The electric and thermal output of the fuel cell are calculated using

$$W_{el} = Q_{input} \cdot \eta_{el}$$

and

$$Q_{th} = Q_{input} \cdot \eta_{th} .$$

General

Apart from the name you can define an operating strategy. Currently, only *heat driven* is implemented: The load point is chosen based on the heat demand and the electricity production is seen as by-product. Consequently, the calculation of fuel cells requires the definition of a Load Curve. Otherwise, the output will be zero.

Rated Conditions

The values stated in this box are for information only. They do not influence the system calculations! Please define the nominal and part load data in the table in the *Nominal and Part Load Data* box.

Nominal and Part Load Data

Here, the actual performance of the fuel cell is defined. Each row of the table allows the definition of a fuel input into the fuel cell with the corresponding thermal and electrical efficiencies. Empty rows are ignored.

Mostly, in the top row the nominal input and efficiencies are states as in the *Rated Conditions* box. The following lines define the part load behaviour. **Please be sure to include also the nominal operation point into the table! Also be sure that the load points are sorted by Qinput in descending order!**

The maximum and minimum values in the table define also the limit of the fuel cell operation. Even if the demand exceeds the maximum load point the actual operation of the fuel cell is limited to the latter. If the demand is below the minimum load point the fuel cell is not operated. In both cases the demand cannot be satisfied.

Some fuel cells may be limited exactly to the given load points with no possibility to operate in between two points. In this case the button *Stepped* should be checked. **greenius** will choose the load point where the heat output is closest to the demand. The alternative is *Variable*, where **greenius** interpolates linearly between two load points in order to operate at just the defined load.

Fuel

The name, price and CO_2 emissions of the fuel can be set here for economic and environmental calculations.

Data Import

The data import component allows the import of hourly power data series of other software programs. The result analysis functions and the economical calculations of **greenius** can be used for these data. This "technology" has only one Component , the Data Import.

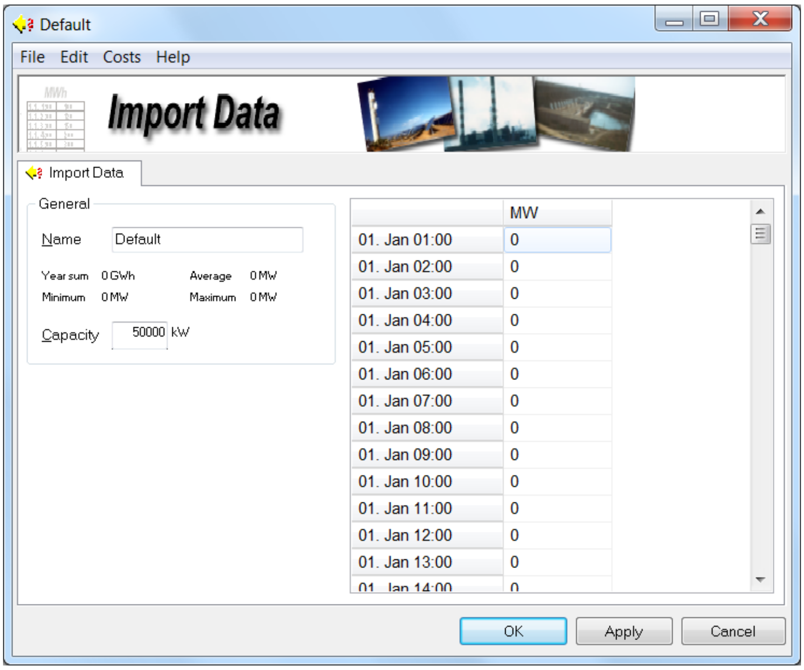
Data Import

The technical parameters for the data import are defined here. They consist only of the rated power and a time series of 8760 hourly average values. The best way is to import the data from an ASCII file.

The parameters of an ASCII file are separated by TAB. The 8760 hourly values are behind each other in a separate row. The ASCII file must have the following format. The capacity must be given in Watt, the hourly import data in MW.

```
name        Standard
capacity    500000000
Res:        365x24

ImportData
30
50
45
50
...
```
(value 8760)



The menu entry *Costs* opens the Import Data costs input window.

Tower with fluctuating el. source

The power tower system with fluctuating electric source allows the annual performance simulation of central receiver solar power plants with a fluctuating electric source, e.g. a PV plant. This enables the calculation of hybrid Tower-PV power plants.

The following components exist for tower power plants:

- Tower system
- Thermal storage

- Powerblock
- Boiler
- External electricity source

External Electricity Source

An external electricity source can be simulated in Greenius, e.g. a PV system. This enables the calculation of hybrid plants. An electric heater or a heat pump can also be included to heat the fluid of the concentrating solar thermal system.

Tab External Electricity Source

The AC electrical output of the external electricity source (show matrix: E_inv,gross) and the parasitics (show matrix: Parasitics) are introduced in the table for each time step. These values can be scaled by a scaling factor. The time step length is also adjustable.

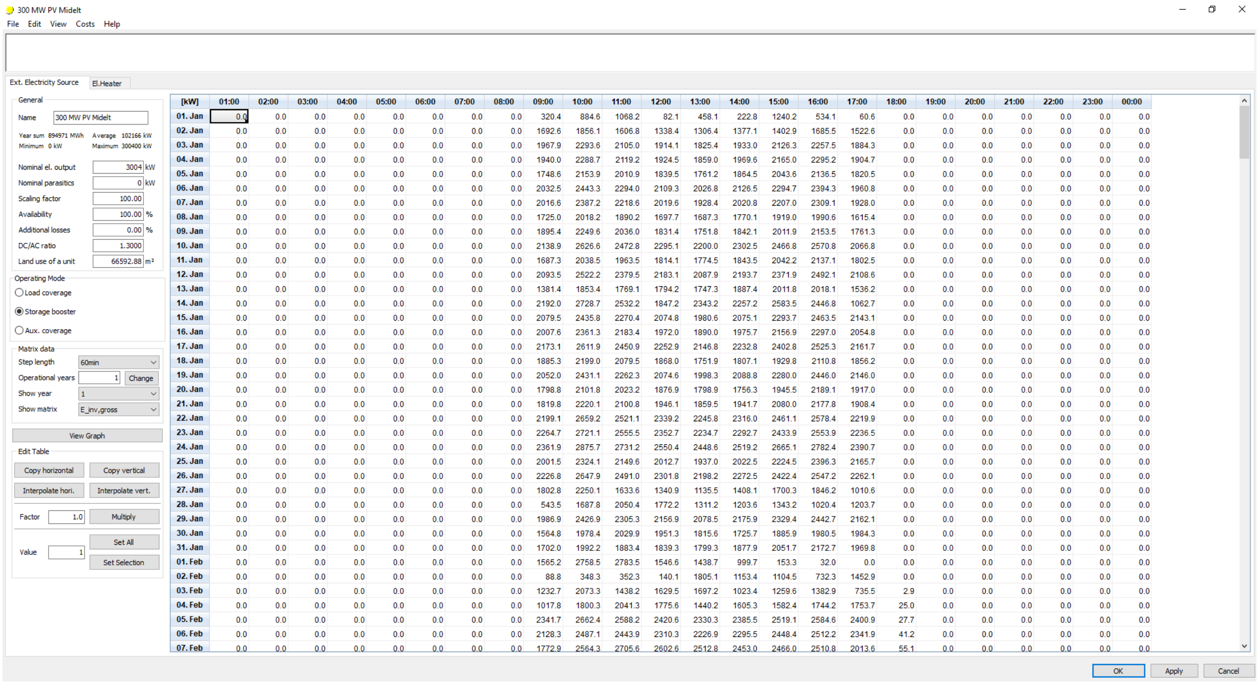
The menu entry *Costs* opens the external electricity source costs input window. The specific costs and the land use to be entered refer to the values of only one unit system. The nominal electrical output, nominal parasitics, availability, additional losses and DC/AC ratio can also be modified.

There are three different operating modes:

- Load coverage: satisfy a load curve. The electric source has the highest utilization priority-

- Storage booster: the electricity is used to bring up the temperature of the molten salt from nominal outlet temperature of the solar field to the nominal temperature of the hot tank, then it is used to cover the auxiliary consumption of the solar field and finally excess electricity may be delivered to the grid. This mode is made for trough plants.

- Aux. coverage: the electricity is primarily used for auxiliary consumption of the solar field, then delivered to the grid and if there is excess electricity, it is used for heating up molten salt from cold tank temperature to hot tank temperature. This mode is for solar towers.



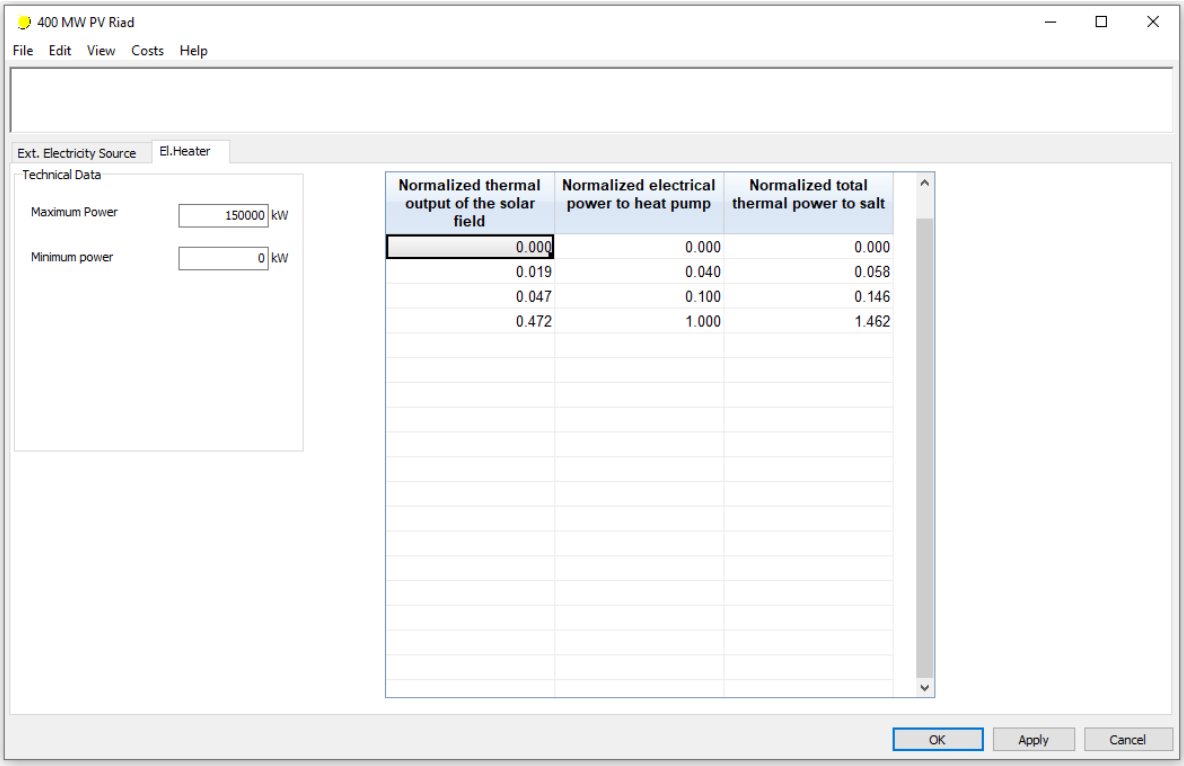
Tab Electric Heater

At the menu entry *View* one of the following options can be chosen:

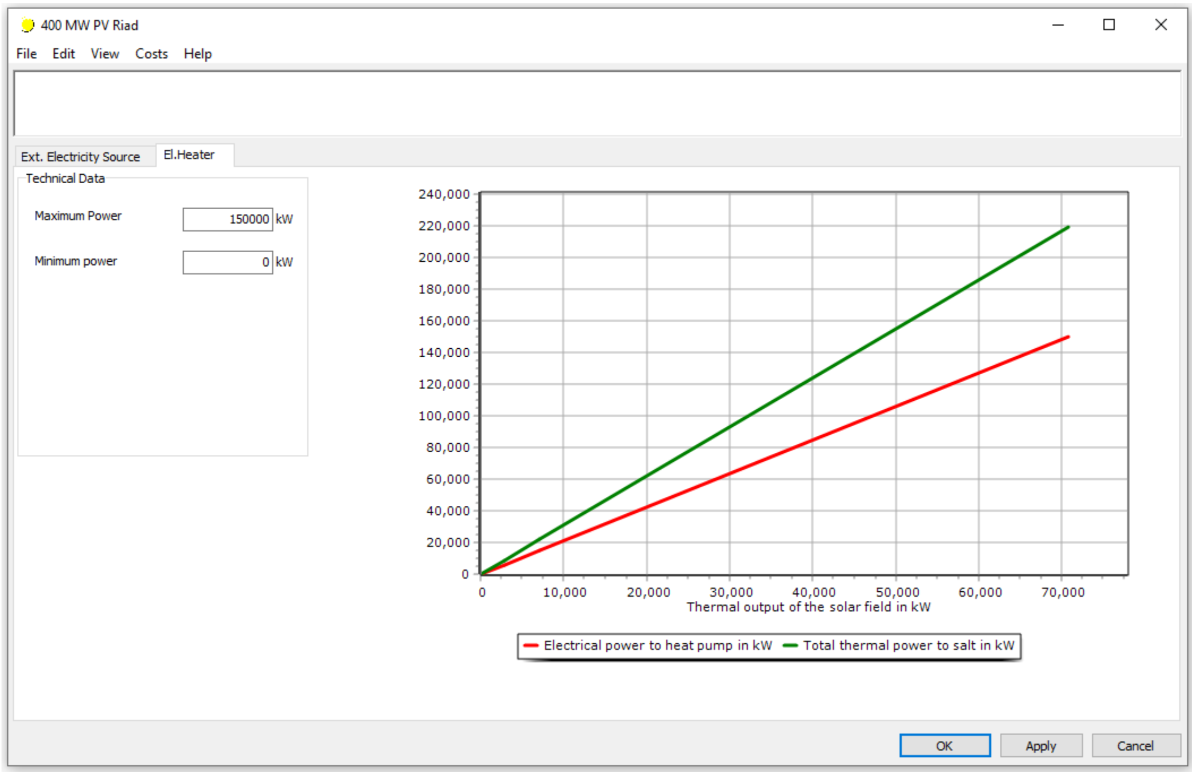
- Table with the characteristic parameters of the electric heater or heat pump.
- Graphic with the characteristic representation of the electric heater or heat pump.

The values of the table are normalized. The real values result from the multiplication of the normalized values by the given maximum power. This maximum power refers to the maximum electric power of the electric heater or heat pump. The first column of the table represents the thermal output of the solar field (parabolic trough or tower system), the second column the electrical power of the electric heater or the heat pump, and the third column the total thermal power transferred to the heat transfer fluid. In the case of a tower hybrid system with a parallel electric heater, only the second and the third column are considered. The third column refers in that case to the total thermal energy supplied by the electric heater to the salt. This energy will be added to the energy supplied by the solar field, which is independent.

The maximum power must be greater than 0 W, otherwise an error occurs.



Data table containing the characteristic parameters of the electric heater



Graphical representation of the electric heater

The menu entry *Costs* opens the electric heater costs input window.

Parabolic Trough with fluctuating el. Source

The parabolic trough system with fluctuating electric source allows the annual performance simulation of parabolic trough solar power plants with a fluctuating electric source, e.g. a PV plant. This enables the calculation of hybrid Parabolic trough - PV power plants.

The following components exist for tower power plants:

- Trough collector
- Trough field
- Thermal storage (in case of the alternative with thermal storage)
- Boiler
- Power block
- External electricity source

Economics

The economics section consists of the following components:

- Costs
- Timing
- Financing

If you like to use the economic features of **greenius** for the output data of another tool, you can use the Data Import technology and perform the economic calculations as you do for all other technologies.

greenius shows the Euro [€] as currency-unit for all financial parameters, and so does this manual. However, the user is not obliged to convert all cost data into Euros. Instead, a currency of choice can be used, but this must be consistent over all components. For pre-defined components delivered with **greenius** it can be necessary to convert the Euro values into the currency of choice. The results always show the €-sign as unit, but actually the values are never converted and use the same currency as the input values.

Costs

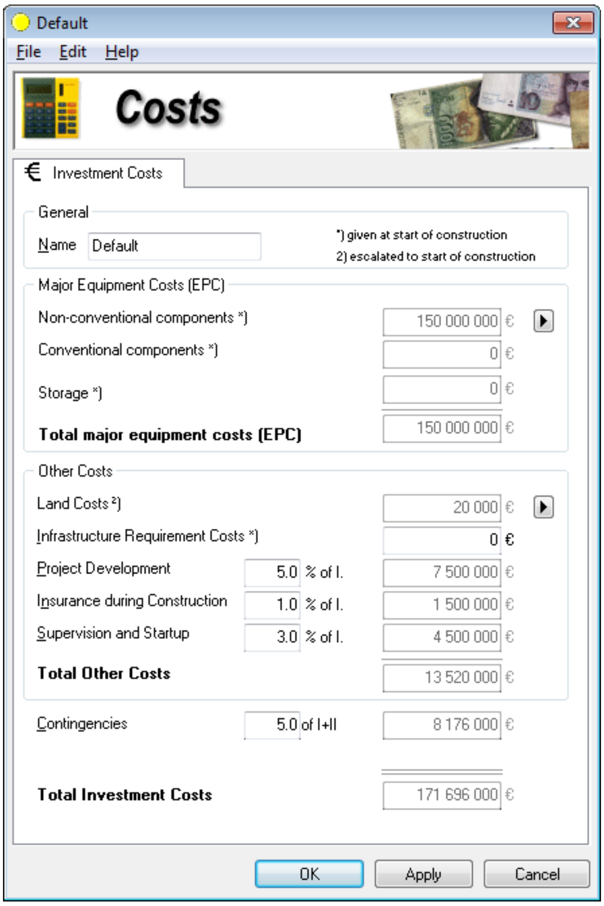
The costs are defined in two different types of forms. The general costs form shows an overview of the investment costs, while the component cost forms show the actual investment and operating cost data of the components.

Costs Form

The costs form gives a summary of all component investment costs within the project. Additionally, some cost surcharges for *project development*, *insurance during construction* and *supervision and startup* can be set.

Major Equipment Costs

The major equipment costs are subdivided into conventional, non-conventional and storage costs. At solar thermal power plants, the solar field is the non-conventional component and the auxiliary boiler and power block are the conventional ones. At PV, wind and Dish/Stirling systems only costs for non-conventional components must be defined. With the triangle button the user can access the component cost form which is described below.



Other Costs

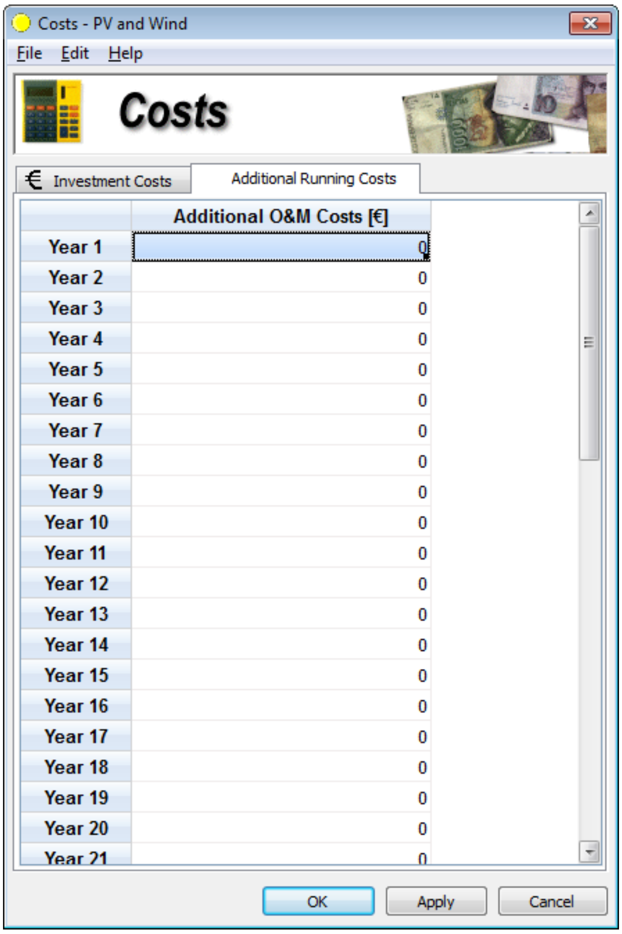
Several additional components of the investment costs are defined in this group:

- *Land Costs* are calculated based on the specific land costs defined in the Location form and the land use which is defined by the technology (e.g. Collector Field)
- *Infrastructure Requirement Costs* can be defined by the user
- *Project Development Costs* , *Insurance Costs During Construction* and *Supervision and Startup Costs* are calculated based on the surcharges defined by the user. They refer to the total EPC costs in the upper box of the form.

Contingencies can be accounted by a surcharge which refers to the sum of total EPC and total other costs. Finally, the Total Investment Costs (CAPEX) including surcharges and contingencies are shown at the bottom of the form. It is calculated automatically and is the base for all further economic analysis.

Additional O&M Costs

The second tabsheet within the cost form allows you to define additional operations and maintenance costs for certain years of the operation of your project. This may for example be necessary if it is planned to replace a battery of a PV system after 12 years while the project itself runs over 25 years. The corresponding costs for the battery replacement can be accounted in the appropriate year by using this feature.



The table supports a maximum project duration of 50 years. If the *operation period* defined in the timing component is shorter all costs defined from year 26 onwards will be neglected.

Component Costs Form

The component costs form can be opened from the general costs form by clicking on the triangle buttons in the upper box. The second possibility is to use the menu entry *Costs|View Costs...*

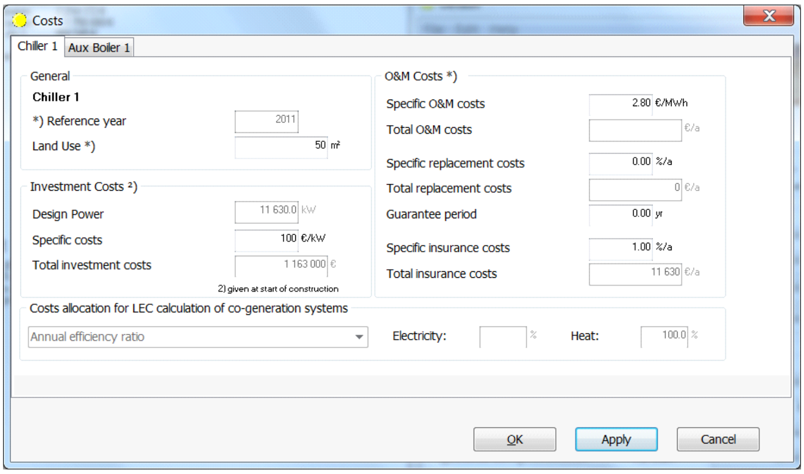
The component costs form allows to modify the specific investment and operating costs for the component it belongs to. For those technologies with more than one (non-)conventional cost component, the component costs form shows one tab for each component (This is only relevant when using the triangle button in the general costs form).

It is very important to notice that the component costs always belong to a certain component and are saved in the relevant component data file. That means, for parabolic trough technology the specific costs for the solar field are stored in the `field.gpa` dataset and for the power block in the `powerblock.gpa`. In order to save modifications to the component cost data the user consequently has to use *File|Save* of e.g. the solar field component. **Using File|Save in the general costs form will only store the surcharge and contingency parameters!**

The component costs are subdivided into

- Investment costs and
- Operating and maintenance costs (O&M).

The investment costs are related to the start of construction, the O&M costs refer to the given *reference year*. Escalation rates are defined in the Nation form.



The following gives an example for the calculation of the component costs for parabolic trough technology.

The total investment costs are calculated using

$$C_i = A_{mir} \cdot c_{sf} + P_b \cdot c_{pb} + P_{ts} \cdot c_{ts} + [A_{sf} + A_{pb}] \cdot c_{land}$$

with the following components

- Solar field costs $= A_{mir} \cdot c_{sf}$ where A_{mir} is the solar field aperture area in m² and c_{sf} is the specific solar field costs including HTF system in €/m²
- Power block costs $= P_{pb} \cdot c_{pb}$ where P_{pb} is the net installed capacity of power block in kW, c_{pb} is the specific costs of power block including turbine, generator, balance of plant in €/kW
- Thermal storage costs $= P_{ts} \cdot c_{ts}$ where P_{ts} is the thermal storage size in MWh and c_{ts} is the specific costs of thermal storage in €/MWh
- Land costs $= [A_{sf} + A_{pb}] \cdot c_{land}$ where A_{sf} is the required land area for the solar field in m², A_{pb} is the land area for the power block in m² and c_{land} are the specific land costs in €/m² (defined in the Location form)

The O&M costs are subdivided into

- General O&M costs (including labour)
- Replacement costs and
- Insurance costs.

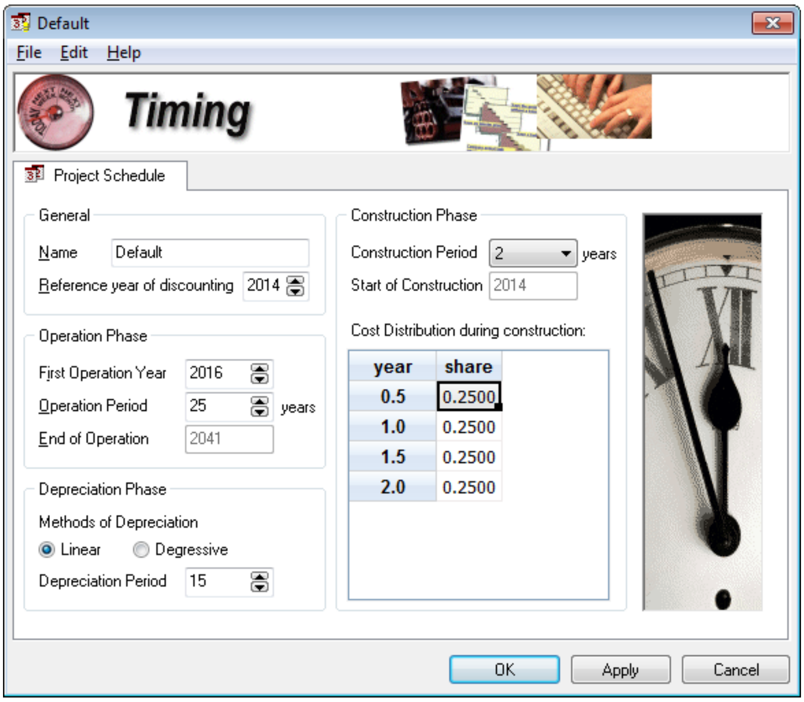
To compute the *operation and maintenance costs*, or the costs associated with the upkeep of the solar field, expenses related to replacement, modifications and upgrades of different parts, along with labour costs must be considered. To compute labor costs, the costs of financing labour in the solar field, power block, and administration must be calculated and summed.

Specific *replacement costs* refer to parts of the plant, which have a limited lifetime or to operating materials, which must be replaced periodically. They are given as specific value based on the total investment costs of the component, this is also valid for *specific insurance costs*.

All costs are given as specific values. If the system size is changed later, these costs are scaled linearly. The user has to keep in mind that particularly the labour costs are not strictly linear with plant size. Instead the number of people needed for administration and power block operation are almost independent of the plant size. This has to be considered by the user and the specific O&M costs must be adapted accordingly.

Timing

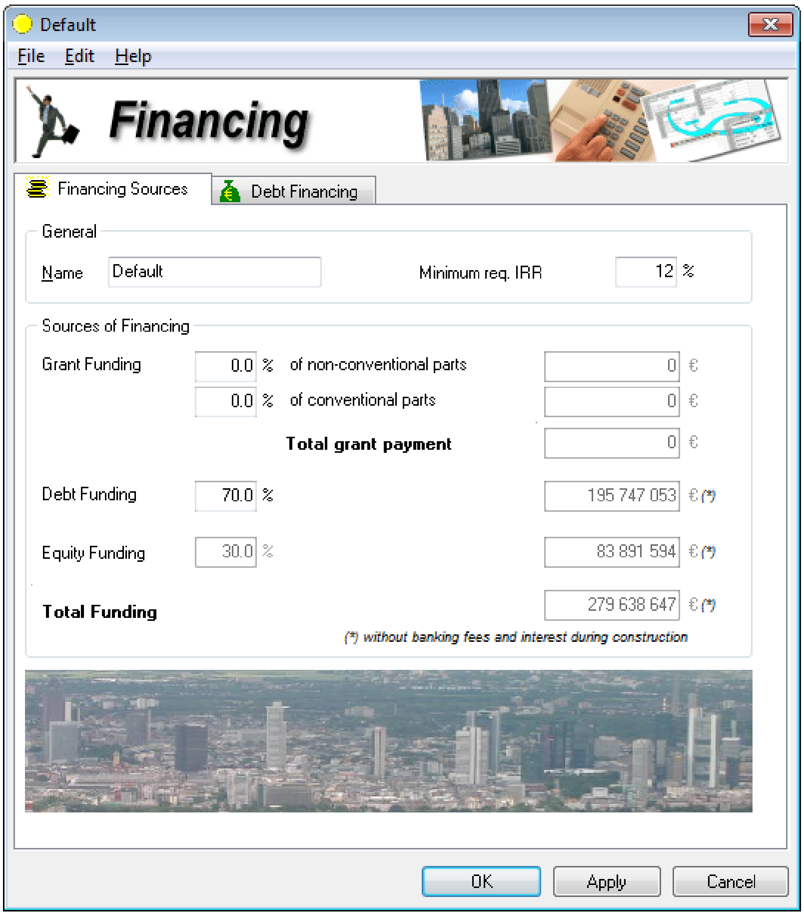
The start of the project and the operation period (economic life time) are defined here. The costs of the construction period can be split into half-year periods. The end of operation and the start of construction are calculated automatically based on the first operation year. The depreciation of the investment costs can be defined as well.



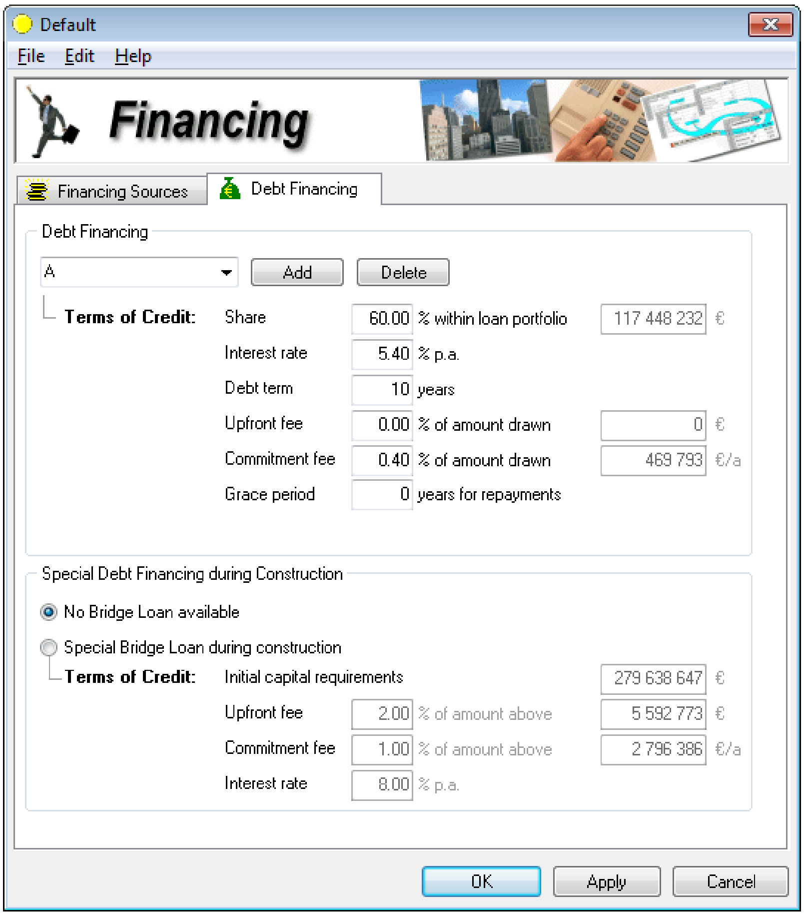
Financing

The economic evaluation of renewable energies usually depends much stronger on the financing conditions compared to fossil alternatives, because the investment costs account for a much higher share of the life time costs of the plant.

The most important financing parameters are defined here. The definition is divided into two tab sheets. The first tab sheet contains general information about grants and the share of equity and loans for the remaining capital requirements. The minimum required IRR (internal rate of return) can be defined as well. This value is needed for the calculation of the required tariff to meet this IRR.



The second tab sheet contains definitions of the loans. Lenders can be added or deleted and the terms of credit can be defined here. A special debt financing during construction is foreseen but not yet implemented.



Simulation and Results

All input parameters of **greenius** are filled with reasonable parameters when creating a new project. Only the technology and a meteorological data file must be chosen. Then, all parameters can be changed and the simulation can be started at any time. This is done at the menu entry *Project Case|Recalculate…* respectively the key *F9*.

The calculation results are presented in three different components:

- Typical Operation Year - Overview of the technical operation of the plant
- Cash Flow - Detailed economic results
- Key Results - Key technical and economic results

These results are presented in separate forms.

All algorithms in greenius have been implemented and tested carefully. However, calculation errors or uncertainties of the used models can never be avoided totally. Furthermore, incorrect or bad chosen input parameters can produce results with high deviations from the reality. It is therefore strictly recommended that specialists verify all simulation results. No liability is accepted for any claims due to wrong simulation results.

In order to enable a complete simulation including investment cost and LEC calculation equipment costs are implemented for all technologies. These values are only rough estimates and no guarantee is given for the accuracy of these values. Each user shall be responsible for the careful examination of the cost assumptions.

Simulation

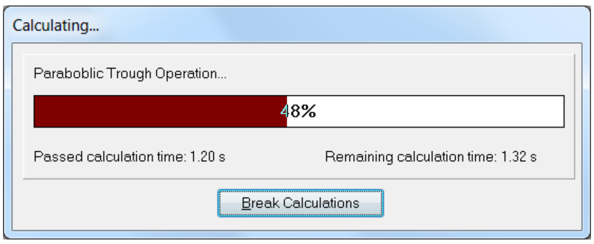
The project simulation in greenius is divided into two steps:

1. Technical Simulation: The defined energy system is simulated for one representative year. It is important to notice that despite an operating time of e.g. 25 years only one year is simulated. This year is referred to as typical operation year (TOY). The results of the TOY are shown in the Typical Operation Year component.
2. Economic Calculation and Post-Processing: The economic evaluation is based on the assumption that the system's performance in each year of operation is equal to the typical operation year. This assumption is reasonable as long as the meteorological data really represents a *typical* year, meaning a long term average, and not just one year of measured data. In some technologies degradation of the system can be included in the post-processing before calculating the economics. This is described in detail below.

A standard simulation can be started with *Project Case|Run Calculation…* respectively *Project Case|Recalculate…* or using *F9*. This starts a complete (re)calculation of the active project. Since it is possible to open several projects at the same time *Project Case|Calculate all Projects…* respectively *Strg+F9* allows to start the (re)calculation for all open projects.

In cases where only financial parameters were changed it is not necessary to recalculate the technical system itself (first step). Therefore, only the second step of the simulation can be triggered by *Project Case|Calculate Economics…* respectively *Shift+F9*. This is very useful for economic parameter variations (e.g. discount rates or financing conditions).

The powerful algorithms of **greenius** allow very fast simulations. Anyway, the user can stop the calculation manually if a run needs more time than expected or due to any other reason.



Technical Simulation

The technical simulation is done for a typical operation year with at least 8760 hourly values. Supported temporal resolutions are 60min, 30min, 20min, 15min and 10min. The time step used for simulation is determined by the temporal resolution of the meteorological data file. The components Load Curve and Operating Strategy (*load* and *strategy*) and Nation (if a *variable remuneration tariff* is used) define parameters for each time step. The resolution of these parameters must match to the meteorological file, otherwise an error message will be shown.

Economic Calculation

The economic analysis is based on the assumption that the performance of the system is the same for each operating year and equal to the simulated typical operation year. However there are some exceptions for certain technologies where post-processing modifications of the TOY are used in order to model certain effects. Those exceptions are described in the following sections.

Degradation

Applicable for Parabolic Trough Power Plants with and without storage, Parabolic Troughs for Process Heat, Parabolic Trough with fluctuating el. Source, Power Towers, Tower with fluctuating el. Source and Grid Connected PV System.

The most important technical output for the economic analysis is the energy (heat or electricity) output of the simulated system. Based on this output the remuneration can be determined. The standard approach is to assume the energy output of the typical operation year from the technical simulation for each operating year. However, some components allow the definition of degradation parameters.

The components Collector Field, Tower Field and PV System offer the possibility to set an annual degradation factor. The default value is 0.0% which corresponds to no degradation at all. In each operating year the energy output of the TOY is expected. For a degradation factor of 0.5% the output in the first year of operation is equal to the TOY output. From the second operating year on the energy output is reduced by 0.5% compared to the previous year (not the TOY).

The degradation factor is nothing more than a post processing reduction of the energy output of the system. In reality, a 0.5% reduction of the solar field output will not lead to 0.5% less electrical output because most solar systems are oversized for the abundant solar irradiation during the summer months.

Post-processing for Countries with a maximum allowed fossil fuel utilization

Applicable for Parabolic Trough Power Plants with and without storage

Some countries have feed-in laws for electricity generated by CSP which allow a certain ratio x_{foss} of fossil fuel utilization on an annual basis. This will increase the total electricity output as well as the plant economics because typically the operators will try to exploit this amount and produce additional electricity which they can sell to the grid for the solar tariff.

During the actual plant operation it is a challenging task to meet the allowed amount of fossil fuel and to optimize its utilization in order to get the optimal electricity output from it. The options are manifold and very plant specific because they depend on plant design and operating strategy. **greenius** offers the option to include such a fixed amount of fossil fuel utilization in the annual calculation by post-processing of the solar-only simulation results.

For this purpose the user must provide the fixed percentage of fossil fuel in the Nation input form. The annual gross electric output from fossil fuel is calculated from this value:

$$W_{gross,foss} = \frac{W_{gross,sol}}{(1 - x_{foss})} - W_{gross,sol}$$

The annual net output from fossil fuel is calculated using the design net/gross output ratio of the individual power block, which is typically in the range of 0.9 to 0.95.

$$W_{net,foss} = W_{gross,foss} \cdot \frac{P_{el,net,design}}{P_{el,gross,design}}$$

The sum of net fossil electricity production and the solar electricity production gives the total annual electricity which can be sold. The annual amount of electricity generated by fossil fuel might not be exactly the value which can be achieved by an optimized operation strategy, e.g. boosting low load operation times of the turbine, but it gives a reasonable estimate.

For the economic calculation the fuel consumption must be calculated which is done by assuming that the conversion from heat to electricity takes place with the mean annual heat to electricity efficiency of the power block. The specific CO_2 production in kg CO_2/kWh of heat is taken from the Powerblock form.

Typical Operation Year

A typical operation year contains detailed technical simulation results. Tables contain all simulation results and important intermediate results. All values are given for the following temporal resolution:

- Hourly (actually based on the current time step and thus according to the temporal resolution of the meteo data file)
- Daily (365 d)
- Weekly (53 Weeks)
- Monthly (12 Months).

The head of the table also contains units, sums and average values (where applicable). The following unit for displaying energies can be chosen at *View|Units|Energy*:

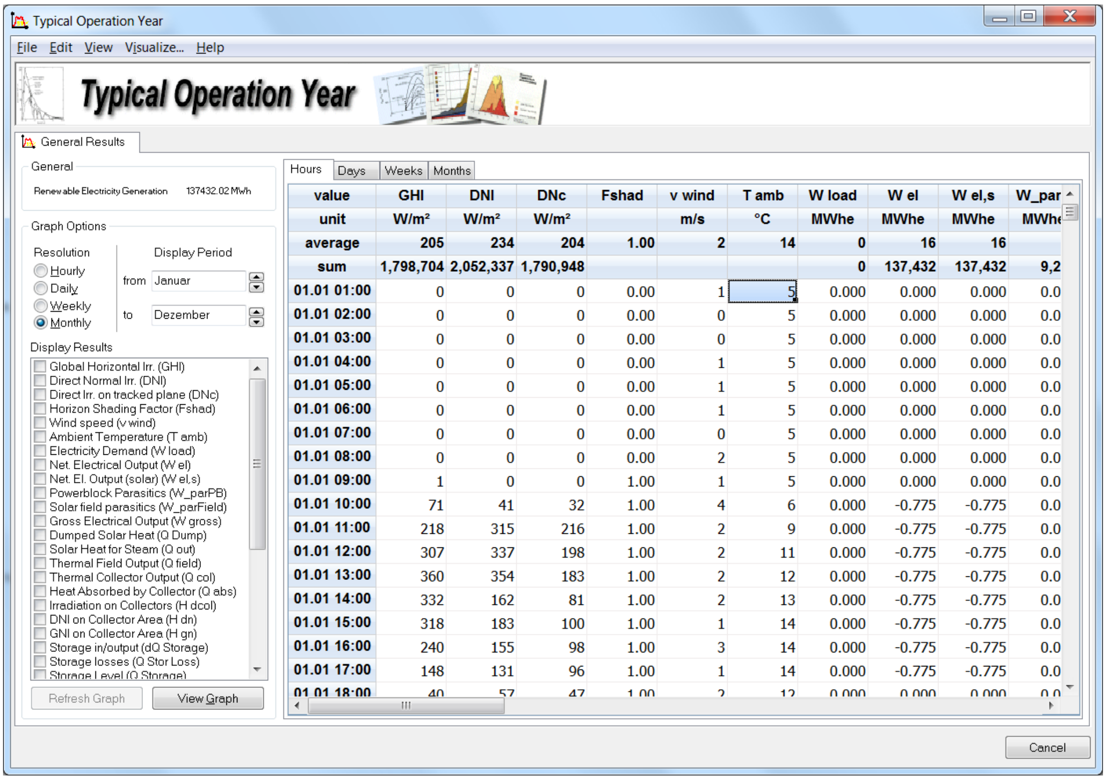
- kWh and
- MWh

The following units for displaying temperatures can be chosen at *View|Units|Temperature:*

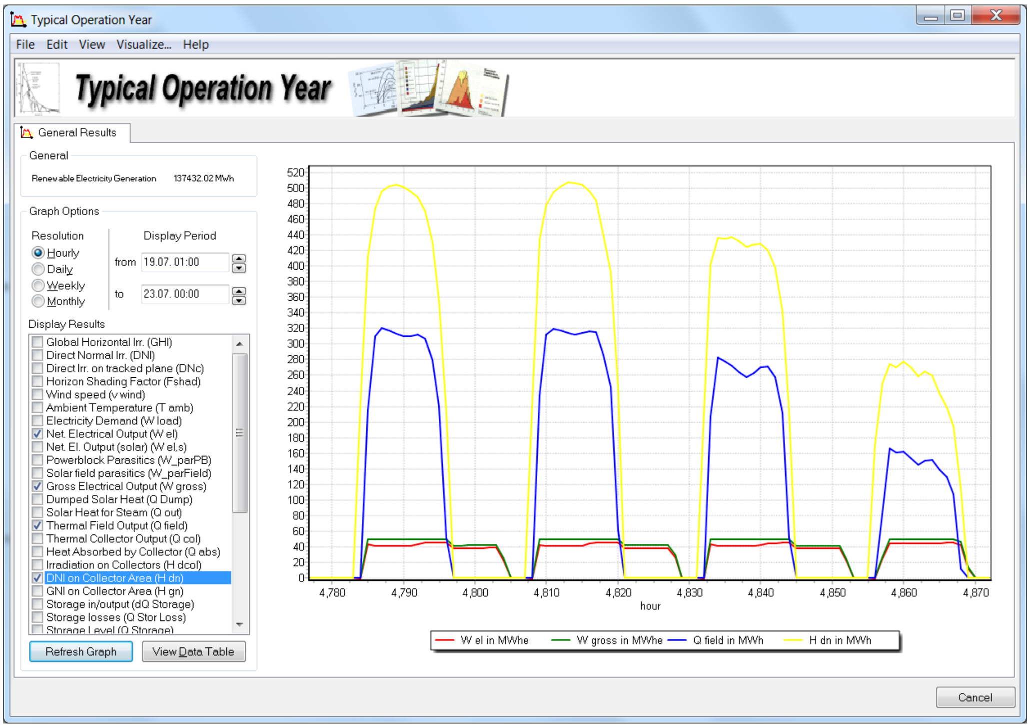
- °C (degrees Celsius)
- °F (degrees Fahrenheit) and
- K (Kelvin)

The unit conversion is done automatically.

All values of the tables can be copied via the Clipboard.



All results can also be displayed graphically. From the list any parameters can be chosen freely. The time period and the time resolution can also be set individually.



After changing the display parameters or the period of time the graphic must be refreshed by pressing the button ↳*Refresh Graph*. With via *right click|Copy* the graphic may be copied to the clipboard.

It is possible to export the data to a prepared Excel workbook for detailed data analysis.

A detailed description of the technical output variables for some technologies is given in the following subsections:

- Output of Parabolic Trough Power Plants
- Output of Solar Tower Systems
- Output of Photovoltaic Plants

Output of Parabolic Trough Power Plants

The following table lists all variables displayed in the *Typical Operation Year* sheet for **parabolic trough solar power plants**. The number and type of output variables depends on the chosen technology, process *heat* vs. *electricity production*. Additionally, some of the variables are only filled with parameters when the enhanced model is used.

Process Heat	Electricity	Unit	Description
GHI	GHI	W/m²	Global Horizontal Irradiance (input data)
DNI	DNI	W/m²	Direct Normal Irradiance (input data)
DNc	DNc	W/m²	Direct Irradiance on tracked plane
Fshad	Fshad	-	Horizon Shading Factor
v wind	v wind	m/s	Wind speed (input data)
T amb	T amb	°C	Ambient Temperature (input data)
Q load		MWh	Heat demand defined by load curve
Q Cool		MWh	Chiller Output
	W load (HV)	MWhe	Electricity demand at high voltage level as defined by load curve
	W load (MV)	MWhe	Electricity demand at medium voltage for the generator of the power block. Should be equal to or higher than W load (HV) in order to compensate for MV->HV transformation losses and transmission losses to grid as defined in power block.
	W el (HV)	MWhe	Total net electrical output at high voltage (from solar and fossil) including transformation and transmission losses
	W el,s (HV)	MWhe	Same as 'W el (HV)' but only solar based generation included
	W_parPB	MWhe	Parasitics by Power Block (power block + cooler + boiler) at MV
	W_parField	MWhe	Parasitics by Solar Field (field + storage) at MV
	W gross	MWhe	Gross electrical output at medium voltage (MV)
Q Dump Load	Q Dump Load	MWh	Dumped solar heat due to load or capacity restrictions of load curve, power block or storage
Q Dump FC	Q Dump FC	MWh	Unavoidable Dumping caused by system configuration (often caused by a too low max mass flow of the recirculation pump (enhanced model) or a too small superheating field compared to evaporator)
Q out	Q out	MWh	Solar heat available for steam production (Q field - Q DumpForced)

Q field	Q field	MWh	Thermal output of solar field (Q col - Q vessel -Q heatlossFB - Q heatupFB)
Q col	Q col	MWh	Thermal collector output (Q abs) - piping heat losses (Qpipe) - receiver heat losses (Qheat) - heat used to increase the mean HTF temperature (Q HeatupSF)
Q abs	Q abs	MWh	Heat absorbed by collectors (H dcol multiplied by the current optical collector efficiency)
H dcol	H dcol	MWh	Irradiation on collectors. This is H dn multiplied by cos(Inc.ang.)
H dn	H dn	MWh	DNI multiplied by time step and total collector area. This value may be interpreted as theoretical solar resource usable by an ideal tracking collector without any losses.
H gn	H gn	MWh	GNI on Collector Area
dQ Storage	dQ Storage	MWh	Storage input/output
	Q Stor Loss	MWh	Storage losses
Q Storage	Q Storage	MWh	Storage Level
Q Boiler	Q_Boiler	MWh	Heat produced by auxiliary boiler (component)
	Q_Aux	MWh	Auxiliary heat delivered by boiler included in the power block (matrix 'auxiliary_heat' in GPA file)
Q s,tot	Q s,tot	MWh	Total solar thermal output used for electricity/heat production
Q th,tot	Q th,tot	MWh	Total thermal output used for electricity/heat production
eta sol	eta th	%	Thermal Field Efficiency (Qout/H dn)
eta fossil	eta tot,s	%	Total Efficiency (W el,s/Hdn)
P el aux		MWh	Parasitics of solar field (field + storage + boiler))
SolSh	SolSh	%	Solar Share
Inc.ang.	Inc.ang.	°	Incidence angle
IAM	IAM	-	Incidence Angle Modifier
T F mean	T HTFmean	°C	Mean HTF Temperature
T F in	T HTFin	°C	Solar field inlet Temperature (only for Enhanced model)
T F out	T HTFout	°C	Solar field outlet Temperature (only for Enhanced model)
mdot F	mdot F	kg/s	Fluid mass flow rate at the solar field inlet (only Enhanced model)
mdot St	mdot St	kg/s	Mass flow leaving the solar field to consumer/PB (for DSG model)
Q Heatup SF	Q Heatup SF	MWh	Variation of heat content in solar field
Q Heatup FB	Q Heatup FB	MWh	Variation of heat content in fluid buffer (only Enhanced model)
Q Heat	Q Heat	MWh	Thermal losses at the heat collecting elements / receiver tubes
Q Pipe	Q Pipe	MWh	Thermal losses at the solar field piping
Q Vessel	Q Vessel	MWh	Thermal losses at expansion vessels / steam drum
Q lossHeatFB	Q lossHeatFB	MWh	Thermal losses at fluid buffer / expansion vessel (Enhanced model)
QFP Stor	QFP Stor	MWh	Freeze Protection from Storage
QFP Aux	QFP Aux	MWh	Freeze Protection from auxiliary Boiler
ItCountPar	ItCountPar	-	Iteration loop counter for parasitic loop
ItCountTemp	ItCountTemp	-	Iteration loop counter for temperature loop
QFFNet	QFFNet	MWh	Net enthalpy entering the system together with the fresh feed

			from external source (only Enhanced model)

Output of Solar Tower Systems

The following table lists all variables displayed in the *Typical Operation Year* sheet for **Solar Tower Plants**.

Variable	Unit	Description
GHI	W/m²	Global Horizontal Irradiance (input data)
DNI	W/m²	Direct Normal Irradiance (input data)
Fshad	-	Horizon shading factor
v wind	m/s	Wind velocity (input data)
T amb	°C	Ambient Temperature (input data)
H dn	MWh	DNI * aperture area
Q max ic	MWh	Maximum intercept heat the field could deliver
Q ic dump	MWh	Intercept heat which must be dumped (to protect the receiver)
Q ic	MWh	Actual intercept heat delivered
mdot HTF	kg/s	Mass flow of heat transfer medium
Q HL pipe	MWh	Heat losses of piping
Q heatup	MWh	Heat used for start up of the tower system (especially receiver)
Q rec	MWh	Heat delivered by the receiver
Q boiler	MWh	Heat from an auxiliary boiler (if installed)
Q aux	MWh	Auxiliary heat from boiler included in power block (matrix 'auxiliary_heat' in GPA file)
dQ Storage	MWh	Heat to/from storage
Q Storage	MWh	Storage content
Q Stor loss	MWh	Storage heat loss
Q out	MWh	Total usable heat delivered by the system
Q pblock	MWh	Heat delivered to power block
Q dump	MWh	Dumped heat (when TES is full and PB runs at maximal load)
W gross CSP	MWh	Gross electricity production of PB
Par TWR	MWh	Auxiliary consumption of the tower system (Control, heat tracing, HTF pumping, etc)
Par TES	MWh	Auxiliary consumption of thermal storage
Par PB	MWh	Auxiliary consumption of power block
Par tot	MWh	Total auxiliary consumption
W load (HV)	MWh	Load demand at high voltage level as defined by the load curve (if applicable)
W load (MV)	MWh	Load demand from power block generator at medium voltage level accounting for expected MV/HV transformation losses and transmission losses to grid (as defined in power block component)
W el (HV)	MWh	Net electric output delivered to the grid at high voltage
W grid (MV)	MWh	Electricity demand from the grid at medium voltage
Q s,tot	MWh	Total solar heat used
Q tot	MWh	Total heat used
eta field	-	Heliostat field efficiency

eta rec	-	Receiver efficiency
eta PB	-	Power block efficiency
eta Tot	-	Total system efficiency
T_PBin	°C	HTF inlet temperature at PB steam generator
T_PBout	°C	HTF outlet temperature of PB steam generator
ItCountPar	-	Number of iterations for the parasitics loop
ItCountTemp	-	Number of iterations for the temperature loop

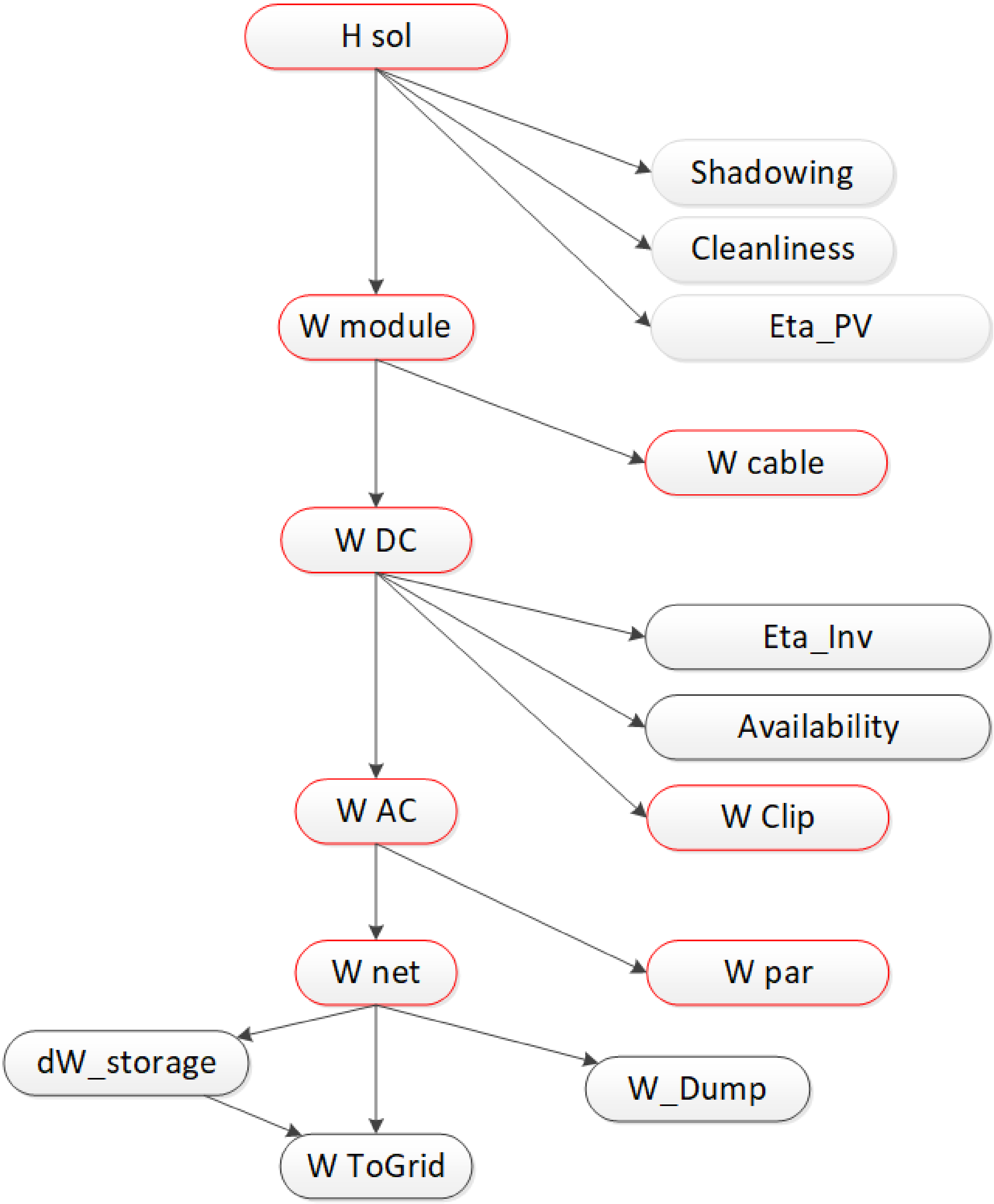
Output of Photovoltaic Plants

The following table lists all variables displayed in the *Typical Operation Year* sheet for **photovoltaic plants**.

Variable	Unit	Description
GHI	W/m²	Global Horizontal Irradiance (input data)
DNI	W/m²	Direct Normal Irradiance (input data)
Diff	W/m²	Diffuse Irradiance (input data)
T amb	°C	Ambient Temperature (input data)
F Dir	-	Direct Shading Factor
F Diff	-	Diffuse Shading Factor
Inc.Ang.	°	Incidence angle on module
D mod	W/m²	Direct Irradiance in module plane on aperture (does not include concentration)
E mod	W/m²	Global Irradiance in module plane on aperture (does not include concentration)
H sol	MWh	Irradiation on module (Irradiation * Aperture; only direct irradiation for concentrating systems, global irradiation for non-concentrating systems)
T cell	°C	Cell temperature
W module	MWh	Output of modules
W cable	MWh	Cable losses
W DC	MWh	DC output (W module - W cable)
W AC	MWh	AC output (W DC * inverter efficiency * availability) Clipping is considered in case of DC input exceeding the max DC input
W Clip	MWh	Losses due to clipping when DC input exceeds the maximum value
W par	MWh	Parasitic losses (for cooling)
W net	MWh	Net Output of PV plant
W load	MWh	Electric load
dW Storage	MWh	Storage input/output
W Storage	MWh	Storage content
W stor loss	MWh	Storage losses
W dump	MWh	Dumped electricity
W ToGrid	MWh	Electricity delivered to grid
R conc	-	Concentrator efficiency
F profile	-	Concentrator profile factor
eta PV	%	Efficiency PV module
eta Inv	%	Efficiency Inverter

eta Sys	%	Overall system efficiency (W AC / H Solar)
PR	%	Performance ratio (W AC / (H Solar * nominal PV efficiency)
IterPar	-	Number of iteration steps for parasitics (if load is defined)
IterTemp	-	Number of iteration steps for source/PV temperature convergence

The following chart visualizes the relation of the different energy related variables to each other:



Cash Flow

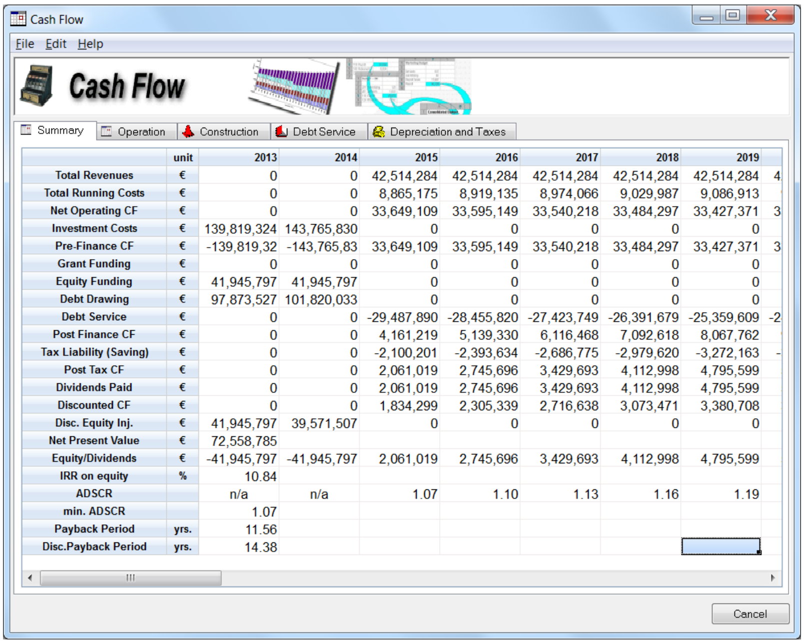
A cash flow analysis is calculated here. Various tab sheets contain detailed cash flows for the following phases respectively parameters:

- Summary
- Operation Phase
- Construction Phase

- Debt Service
- Depreciation and Taxes

Important financial parameters such as the LEC and ADSCR are calculated and displayed as well.

The contents of the tables can be copied via the Clipboard.



	unit	2013	2014	2015	2016	2017	2018	2019
Total Revenues	€	0	0	42,514,284	42,514,284	42,514,284	42,514,284	42,514,284
Total Running Costs	€	0	0	8,865,175	8,919,135	8,974,066	9,029,987	9,086,913
Net Operating CF	€	0	0	33,649,109	33,595,149	33,540,218	33,484,297	33,427,371
Investment Costs	€	139,819,324	143,765,830	0	0	0	0	0
Pre-Finance CF	€	-139,819,32	-143,765,83	33,649,109	33,595,149	33,540,218	33,484,297	33,427,371
Grant Funding	€	0	0	0	0	0	0	0
Equity Funding	€	41,945,797	41,945,797	0	0	0	0	0
Debt Drawing	€	97,873,527	101,820,033	0	0	0	0	0
Debt Service	€	0	0	-29,487,890	-28,455,820	-27,423,749	-26,391,679	-25,359,609
Post Finance CF	€	0	0	4,161,219	5,139,330	6,116,468	7,092,618	8,067,762
Tax Liability (Saving)	€	0	0	-2,100,201	-2,393,634	-2,686,775	-2,979,620	-3,272,163
Post Tax CF	€	0	0	2,061,019	2,745,696	3,429,693	4,112,998	4,795,599
Dividends Paid	€	0	0	2,061,019	2,745,696	3,429,693	4,112,998	4,795,599
Discounted CF	€	0	0	1,834,299	2,305,339	2,716,638	3,073,471	3,380,708
Disc. Equity Inj.	€	41,945,797	39,571,507	0	0	0	0	0
Net Present Value	€	72,558,785						
Equity/Dividends	€	-41,945,797	-41,945,797	2,061,019	2,745,696	3,429,693	4,112,998	4,795,599
IRR on equity	%	10.84						
ADSCR		n/a	n/a	1.07	1.10	1.13	1.16	1.19
min. ADSCR		1.07						
Payback Period	yrs.	11.56						
Disc.Payback Period	yrs.	14.38						

The following equations show how the economic figures of merit defined.

Net Present Value

The net present value *NPV* is the difference between the present value of revenues (R_t) and present value of costs (C_t) over the project lifetime (n). It helps to determine the attractiveness of an investment depending on the discount rate *d*. A positive NPV is seen as attractive to investors.

$$NPV = \sum_{t=1}^{n} [(R_t - C_t) \cdot (1+d)^{-t}]$$

The *NPV* is heavily dependent on discount rate, which varies from project to project from anywhere between 5-10% and even more. The discount rate is set in the Nation form.

Annual debt service coverage ratio

The annual debt service coverage ratio is used to analyse the project's ability to bear the debt burden, where $CF_{pf,t}$ is pre-finance cash flow, $C_{tax,t}$ is tax payment, and $D_{s,t}$ is debt service in year t.

$$ADSCR_{min} = min\left[\frac{(CF_{pf,t} - C_{tax,t})}{D_{s,t}}\right]$$

Lenders normally claim that the ADSCR must never fall short of the minimum threshold during the lifetime of the project. (Usually the minimum threshold is between 1.2 -1.5, but depends on the specific project)

Payback period

The payback period is a simple indicator to evaluate whether a project is favourable. It calculates the time limit *n* in which the accumulated dividends Div_t paid to the equity investor are equal to the initial investment $C_{i,t}$. The project with the fewest years to payback is the most attractive one to pursue.

$$\sum_{t=1}^{n} C_{i,t} = \sum_{t=1}^{n} Div_t$$

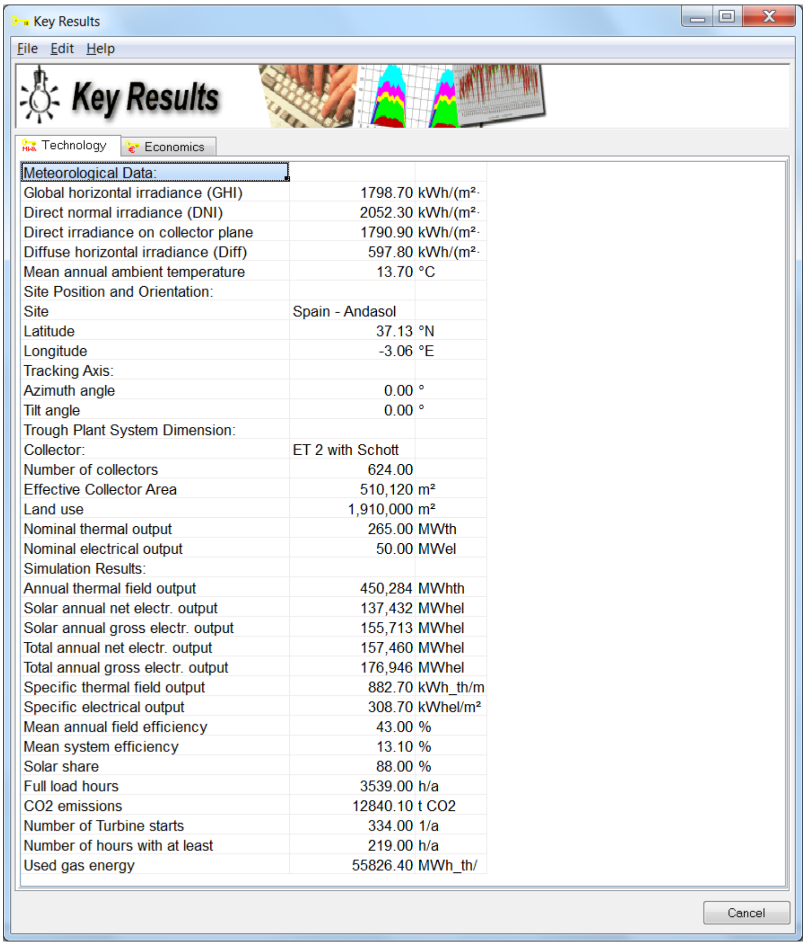
For longer time horizons, the discounted payback method is used where $C_{i,t}$ and Div_t are discounted with the discount rate *d*. Since the investment is closer to the present than the dividend payments, the discounted payback period is higher than the non-discounted one.

$$\sum_{t=1}^{n} \frac{C_{i,t}}{(1+d)^t} = \sum_{t=1}^{n} \frac{Div_t}{(1+d)^t}$$

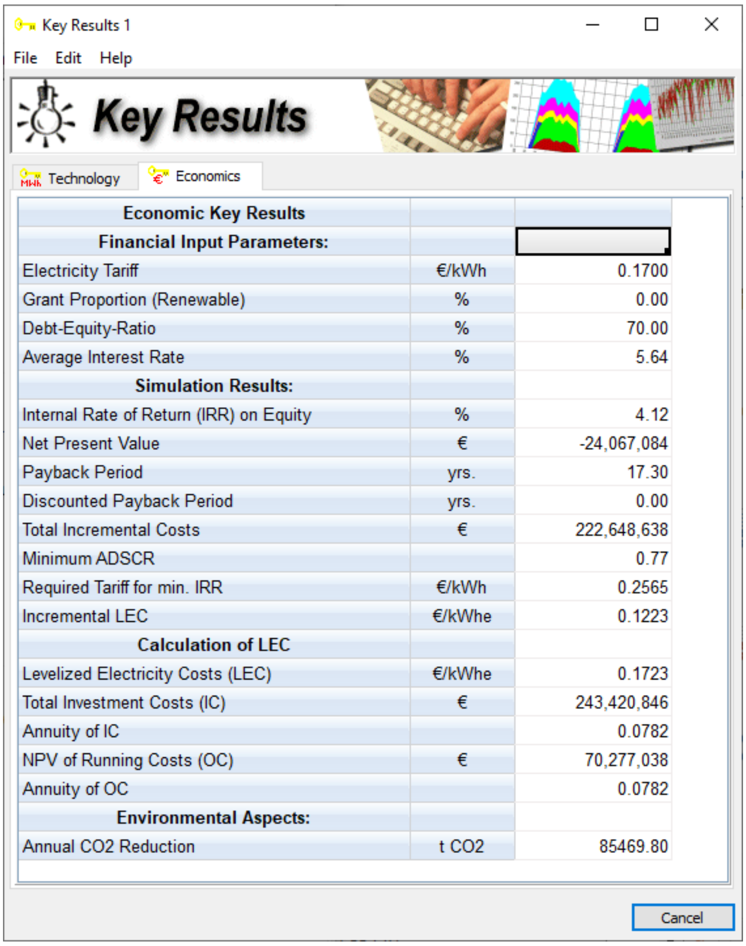
Key Results

A summary presents the most important parameters in two separate tab sheets for technological and economical parameters.

The values of the tables can be copied via the clipboard to other applications. All tables can also be printed or saved in various formats via the menu entries *File|*
Print Active Data Table… or *File|Save Active Data Table As….*



Meteorological Data:		
Global horizontal irradiance (GHI)	1798.70	kWh/(m²·
Direct normal irradiance (DNI)	2052.30	kWh/(m²·
Direct irradiance on collector plane	1790.90	kWh/(m²·
Diffuse horizontal irradiance (Diff)	597.80	kWh/(m²·
Mean annual ambient temperature	13.70	°C
Site Position and Orientation:		
Site	Spain - Andasol	
Latitude	37.13	°N
Longitude	-3.06	°E
Tracking Axis:		
Azimuth angle	0.00	°
Tilt angle	0.00	°
Trough Plant System Dimension:		
Collector:	ET 2 with Schott	
Number of collectors	624.00	
Effective Collector Area	510,120	m²
Land use	1,910,000	m²
Nominal thermal output	265.00	MWth
Nominal electrical output	50.00	MWel
Simulation Results:		
Annual thermal field output	450,284	MWhth
Solar annual net electr. output	137,432	MWhel
Solar annual gross electr. output	155,713	MWhel
Total annual net electr. output	157,460	MWhel
Total annual gross electr. output	176,946	MWhel
Specific thermal field output	882.70	kWh_th/m
Specific electrical output	308.70	kWhel/m²
Mean annual field efficiency	43.00	%
Mean system efficiency	13.10	%
Solar share	88.00	%
Full load hours	3539.00	h/a
CO2 emissions	12840.10	t CO2
Number of Turbine starts	334.00	1/a
Number of hours with at least	219.00	h/a
Used gas energy	55826.40	MWh_th/



Economic Key Results		
Financial Input Parameters:		
Electricity Tariff	€/kWh	0.1700
Grant Proportion (Renewable)	%	0.00
Debt-Equity-Ratio	%	70.00
Average Interest Rate	%	5.64
Simulation Results:		
Internal Rate of Return (IRR) on Equity	%	4.12
Net Present Value	€	-24,067,084
Payback Period	yrs.	17.30
Discounted Payback Period	yrs.	0.00
Total Incremental Costs	€	222,648,638
Minimum ADSCR		0.77
Required Tariff for min. IRR	€/kWh	0.2565
Incremental LEC	€/kWhe	0.1223
Calculation of LEC		
Levelized Electricity Costs (LEC)	€/kWhe	0.1723
Total Investment Costs (IC)	€	243,420,846
Annuity of IC		0.0782
NPV of Running Costs (OC)	€	70,277,038
Annuity of OC		0.0782
Environmental Aspects:		
Annual CO2 Reduction	t CO2	85469.80

LEC (Levelized Electricity Cost)

An accepted way to compare technologies is through Levelized Cost analysis which spreads all costs over the lifetime of the project. In **greenius** Levelized Electricity Electricityvare calculated.

LEC levelizes the present value of future costs discounts future costs and revenues.

$$\boldsymbol{LEC = \frac{Total\ Investment\ Costs + \sum_{t=1}^{n} \frac{Annual\ Running\ Costs_t}{(1 + r_{O\&M})^t}}{\sum_{t=1}^{n} \frac{Annual\ Electricity\ Solar_t \cdot (1-d)^{t-1}}{(1 + r_I)^t}}}$$

With:

$Annual\ Running\ costs = C_{O\&M,t} + C_{rep,t} + C_{fuel,t} + C_{el\_grid,t} + C_{water,t} + C_{insurance,t}$

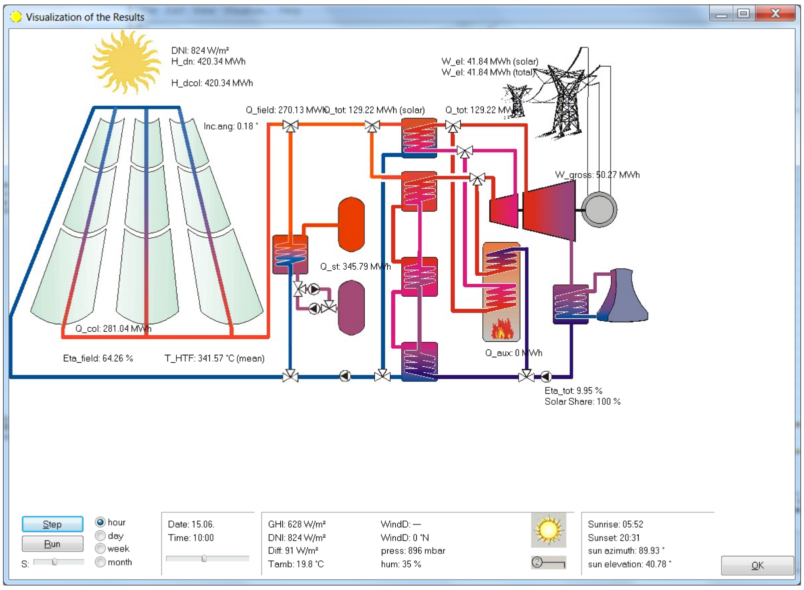
r_I = discount rate for investment costs defined on the Nation form

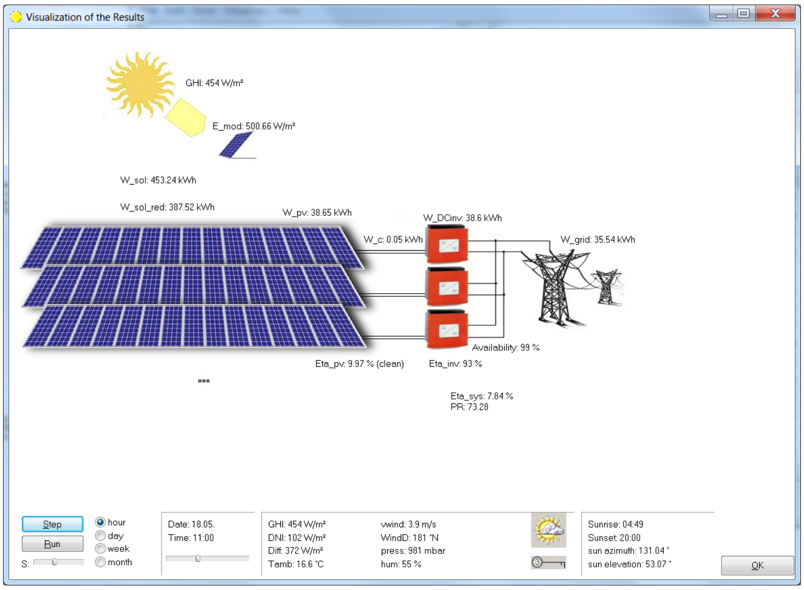
$r_{O\&M}$ = discount rate for investment costs defined on the Nation form

Typically discount rates for investment and O&M will have identical numerical values.
LEC calculates the life-cycle cost per unit of energy delivered to the grid. The project with the lowest LEC provides the most favourable solution.

Visualiser

greenius has a powerful visualization tool. All results can be shown graphically here. This tool is perfectly suited for online presentations or teaching purposes. It can be started in the Typical Operation Year form with *Visualize...*





Collaboration with other applications

greenius offers respectively requires the collaboration with other tools, e.g. result tables can be copied to the clipboard and meteo data is imported from other software. The various interfaces to other tools are described in the following subsections.

Excel Export

The results of a **greenius** simulation are displayed in three components:

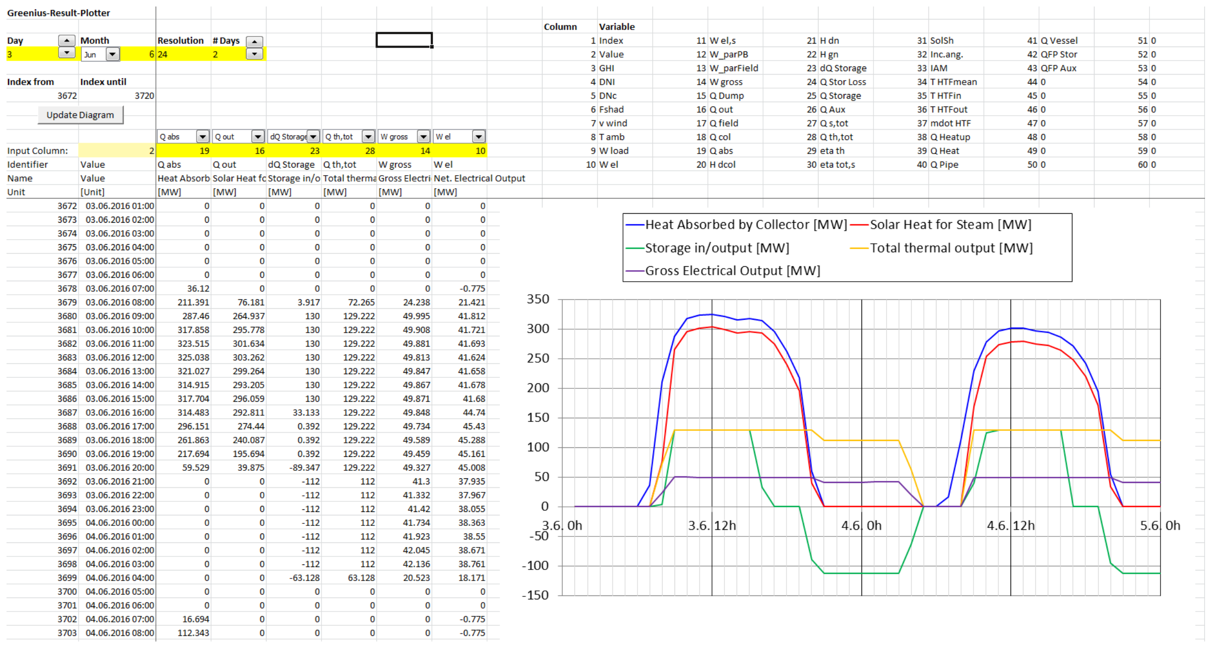
- The Typical Operation Year (TOY) for technical results
- The Cash Flow for economic results
- The Key Results gives an quick overview of technical and economic results

In general, all grids can be exported manually using the Clipboard functions. Additionally, **greenius** provides more sophisticated export functions for Typical Operation Year and Cash

Flow data: Via File|Save Active Data Table as... you can export the whole grid to a `*.xls` file. The second export method allows the export to a prepared Excel file which allows easy data analysis with pre-defined diagrams. This export method is only used for Typical Operation Year and described in the following.

Greenius Excel Plotter

The greenius Excel plotter allows quick, easy and extensive analysis of the technical results presented in Typical Operation Year. It can be accessed via *File|Export to Excel-Plotter* or *File|Export to and Show Excel-Plotter*. The screenshot below shows the actual plotter sheet of the workbook.



In general, cells with yellow background are supposed to be modified by the user. In the main plotter sheet you will usually want to specify the day and month as well as the included variables of the plot. Additionally, you may choose to plot several days in a row. The workbook works also for 10min time steps, but in this case with a maximum number of three days that can be displayed in the diagram. For longer time steps the maximum number of days is limited to the equivalent number of data rows (e.g. 20min -> 6 days).

When you open the plotter for the first time it may be necessary to allow macros for this workbook. Otherwise, the automatic modification of the charts will not work properly. Additionally, a click on *Update Diagram* may be needed.

The sheet *Plotter_DWM* is similar to the *Plotter* sheet, but is used for daily, weekly or monthly values. By default, monthly data is copied to this sheet. If you desire to analyse weekly or daily values just use the Clipboard to copy data from **greenius** into the *Input_DWM* sheet.

At some point it is probably necessary to modify the data ranges of the diagrams in order to show less than six variables or more rows of data in the *Plotter_DWM*. Do so by clicking on the diagram and then adjusting the coloured rectangles representing the data ranges.

You may also insert customized data into both input sheets *Input* and *Input_DWM*, but be sure not to overwrite the first column with the index values. Keep also in mind, that the first four rows are header rows. Row five is the first data row. If you have data with less header rows, insert it accordingly.

In the sheets *VariableTable* and *VariableTable_DWM* you may define which header row in the input sheets contains the variable name and which one the according unit. This is usually not necessary if the source data is exported from **greenius**. More useful is the possibility to define a custom name for each variable in column D of the variable table sheets.

Customized Excel Plotter

You may design your own Excel plotter file if desired and use it as template for your copy of **greenius**. For example, you can add additional diagrams either to the original plotter sheet or you use a copy of the plotter sheet in order to work with different sets of variables. Afterwards, overwrite (after storing a backup of the original) `GreeniusPlotter.xlsm` in the **greenius** root directory. Your customized version is now the basis for all exports to the excel plotter.

Clipboard

greenius offers very extensive export possibilities. Almost all graphics and table contents can be copied to other applications such as MS-Word or MS-Excel.

Tables can best be copied via the clipboard (⌨*Ctrl+C* and ⌨*Ctrl+V*) to other applications. The whole table can be marked using ⌨*Ctrl+A* or clicking to one of the fixed cells in the upper left corner of the table. Whole rows and columns can be marked by clicking on the fixed cells at the top of a column or at the beginning of a row. Some tables in **greenius** are used to define parameters. Data from the clipboard can be pasted with ⌨*Ctrl+V*.

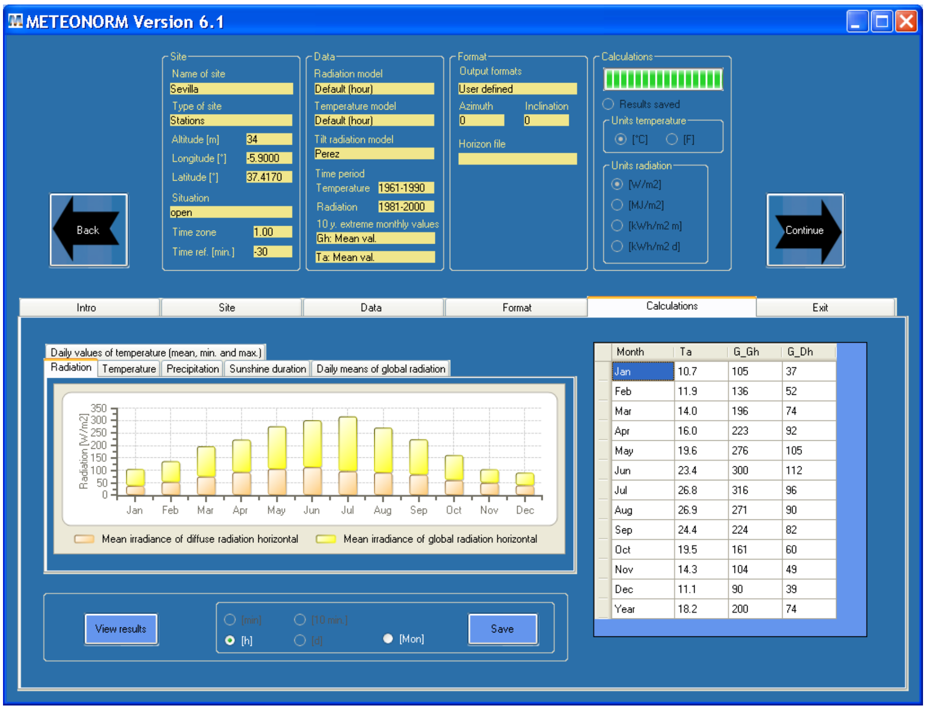
Charts are best copied to the clipboard with *right click|Copy*.

Create Meteo Data with METEONORM

Some meteorological data files are included in the full **greenius** version. However, you might have the problem to get meteorological data sets especially for your site. The software program METEONORM of the Meteotest company can help at this problem. The following steps describe how to create a **greenius** meteo file with METEONORM. The steps and screenshots given here correspond to the version 6.1 of METEONORM but should also work with newer versions.

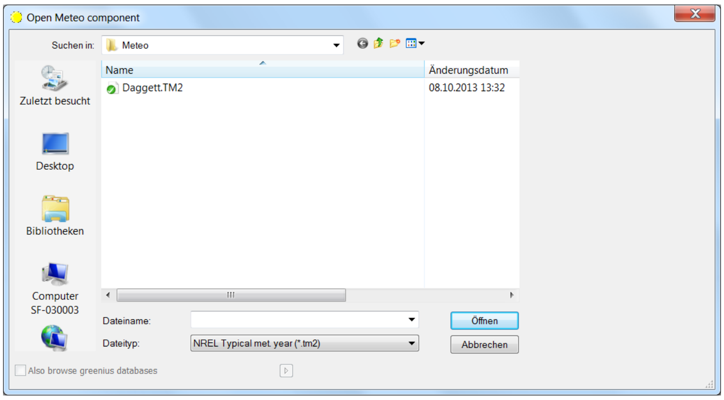
- Start METEONORM
- Choose the desired site
- On the tab "Data" press the button ↳*Default values*
- Select the tab "Format"

- Select the option “Output formats” – “TMY2”.
- Go to the “Calculation” tab and the dataset will be calculated:



Use the button *Save* to save the calculated data to a *.tm2 file.

greenius is capable to read this file using the intrinsic TMY2 import function which is accessible in the *open file* dialog were the user may chose the file type “***.tm2**”. The *open file* dialog occurs when the *Load* button is pushed or the menu entry *File|Load* is activated.



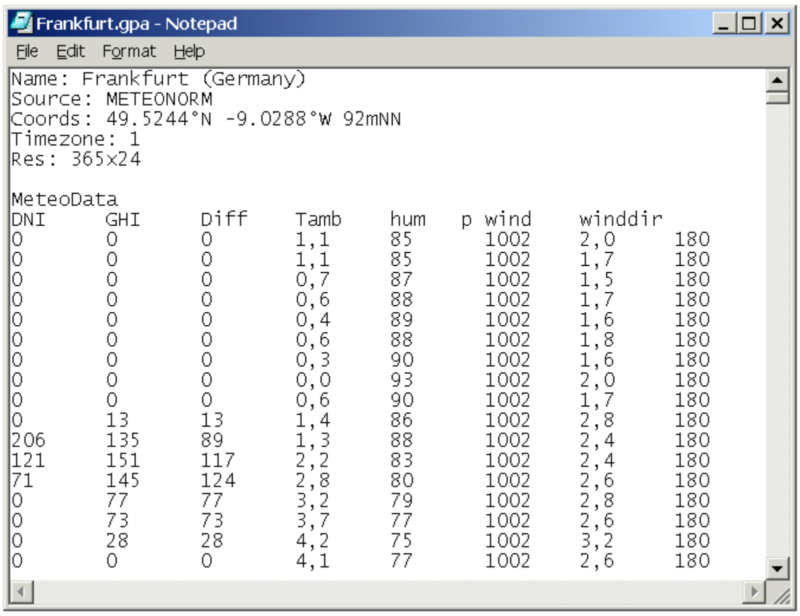
Further information about METEONORM and prices you will find in the Internet at http://www.meteonorm.com

Alternatively the output file from METEONORM may be edited manually to a format given below:

Headers of each **greenius** meteo file have the following format:

```
Name: Location name
Source: Any additional information
Coords: latitude  longitude  height above sea level
Timezone: time zone
Res: 365x24
Empty line
MeteoData
column headings (identifier separated with TAB)
```

Keywords must be typed exactly in the way given here and values must be separated by tab stops. Meteorological files delivered with **greenius** may be used as template for new ones. Note that **greenius** uses positive values for North, and East! The longitude for Frankfurt in the following example can be defined either as
-9.0288°W or as 9.0288°E.




```
Name: Frankfurt (Germany)
Source: METEONORM
Coords: 49.5244°N -9.0288°W 92mNN
Timezone: 1
Res: 365x24

MeteoData
DNI     GHI     Diff    Tamb    hum    p wind   winddir
0       0       0       1,1     85      1002    2,0     180
0       0       0       1,1     85      1002    1,7     180
0       0       0       0,7     87      1002    1,5     180
0       0       0       0,6     88      1002    1,7     180
0       0       0       0,4     89      1002    1,6     180
0       0       0       0,6     88      1002    1,8     180
0       0       0       0,3     90      1002    1,6     180
0       0       0       0,0     93      1002    2,0     180
0       0       0       0,6     90      1002    1,7     180
0       13      13      1,4     86      1002    2,8     180
206     135     89      1,3     88      1002    2,4     180
121     151     117     2,2     83      1002    2,4     180
71      145     124     2,8     80      1002    2,6     180
0       77      77      3,2     79      1002    2,8     180
0       73      73      3,7     77      1002    2,6     180
0       28      28      4,2     75      1002    3,2     180
0       0       0       4,1     77      1002    2,6     180
```

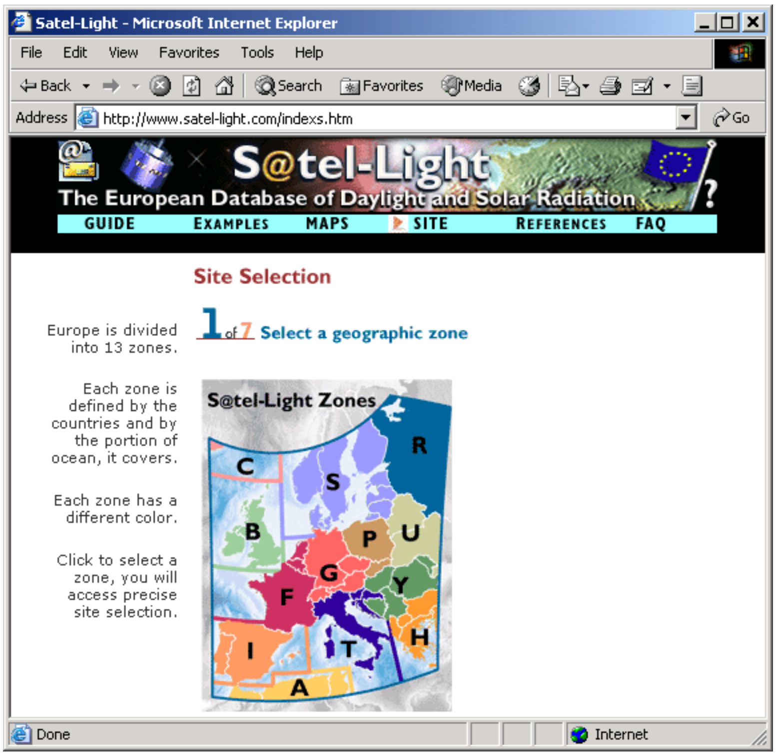
Of course you can also use other sources for meteorological data to generate **greenius** meteo files. However, the format must be same as the above-described **greenius**-gpa-format, otherwise **greenius** will not accept this file.

Sometimes satellite derived meteorological data is provided with time information based on UTC. It is very important that **greenius** is using local time of the relevant site and therefore the hourly values must be shifted accordingly. The first line containing actual hourly data in **greenius** (line 9 of the *.gpa) is for the first hour of the year, that means for 00:00 to 01.00 of 1st January.

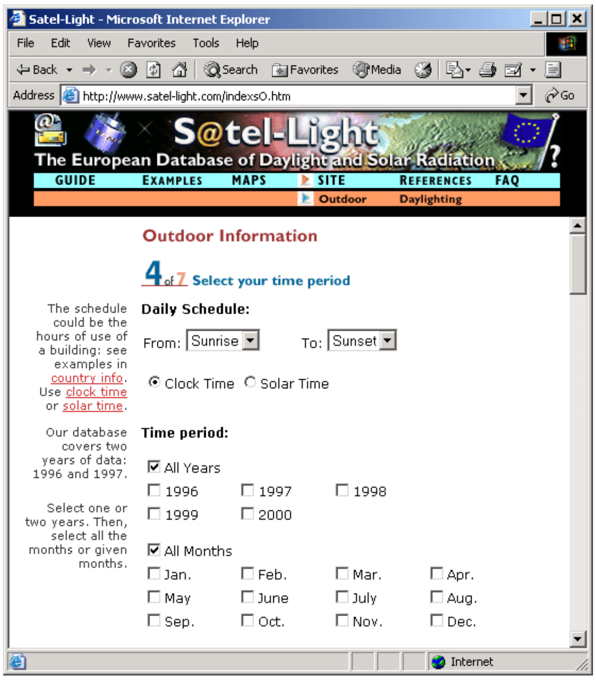
Import Meteo Data from S@tel-Light

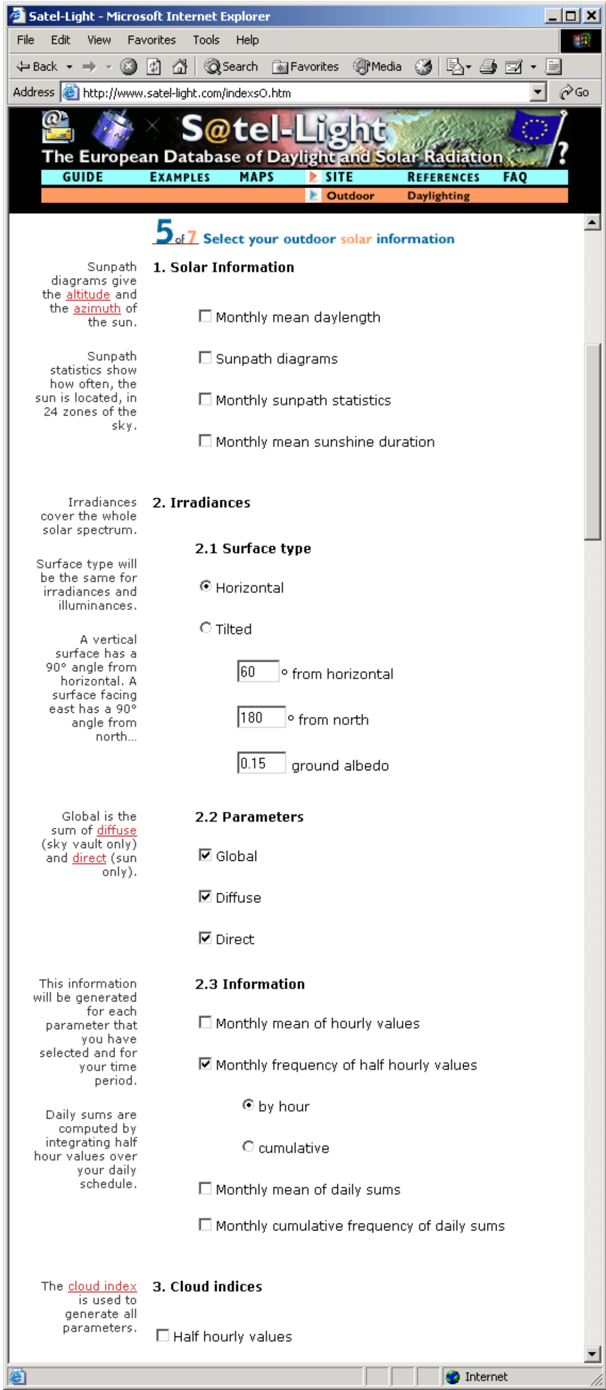
S@tel-Light is an Internet database that can generate free irradiation datasets for Europe and neighboured regions from satellite images. **greenius** has a powerful import filter that can import these TSV files directly.

To generate a TSV irradiance file start S@tel-Light and login. At the menu entry *Site you* can choose a geographic zone and a site.



After you have chosen a geographic zone and a site you can define at step 4 what years you would like to receive. It is recommended to keep the standard values. At step 5 the settings shown in the following screenshot on the right should be chosen.





No fields should be marked at Step 6. After pressing ✎*SUBMIT* the data file is generated. You get an e-mail with a link on the website from where you can download the data file in the ZIP-format. Unpack the TSV file at your computer. Now you can load the TSV file directly as meteo component if you chose the file type *.tsv.

If multiple years are inside the S@tel-Light data file, you can choose the year you want to import. Since **greenius** cannot process leap years the 29th of February of these years will be deleted. Missing hour values are left empty.

Import Meteo Data from NSRDB

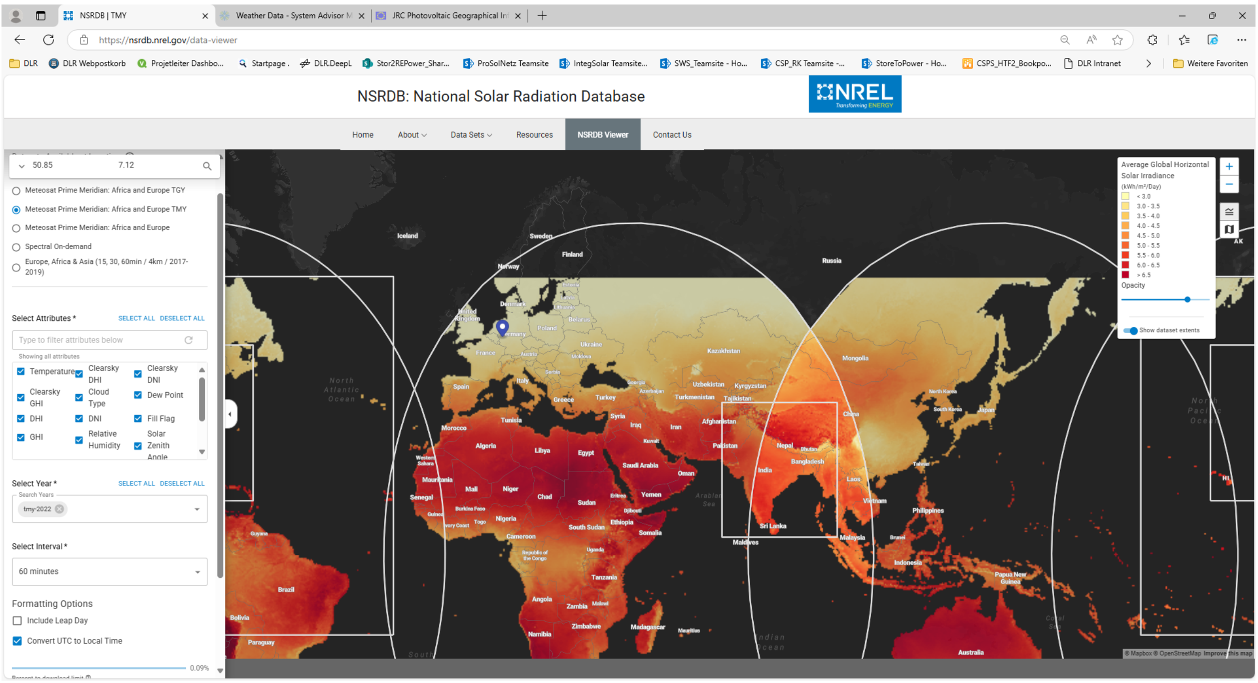
Free typical meteorological year (TMY) datasets with the required hourly resolution and the required solar radiation parameters can be downloaded from NRELs National Solar Radiation Database (NSRDB): https://nsrdb.nrel.gov/data-viewer

Although the title implies that these are only datasets for sites in USA, they offer data for many sites all over the world. Users need to choose the site, the desired information, and to provide their email address and shortly after submitting the request, they will get a download link to fetch the data file.

These files are comma separated (*.csv) and use the SAM meteo input format.

The figure below shows a screenshot of the website with recommended user inputs:

- Latitude and longitude of the site (these values may also be chosen by setting a marker in the map)
- TMY dataset
- Select all attributes (**greenius** will pick those which are actually needed during the data import)
- Year: tmy2022
- 60 minutes
- Convert UTC to Local Time



Run greenius from Command Line

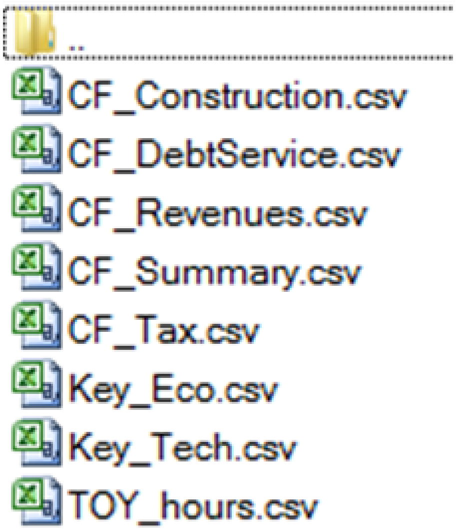
Simulations at fine temporal resolution can cause significant simulation times. Combined with extensive parameter variations this can result in long periods of time where the user starts one simulation after another. The possibility to start **greenius** from command line is a key feature to get automated parameter variations.

For the command line start just switch to the greenius installation directory and use the command below:

```
cd d:\Programme\Greenius
greenius.exe d:\projectFile.gpj d:\outputPath\
```

The two required parameters are the location of the projectFile that shall be simulated and the directory where the simulation results shall be saved. No graphical user interface will show up. At the end of the simulation you will find the following result tables as `*.csv` files in the output directory:

- Hourly resolution of Typical Operation Year
- All tables of Cash Flow component
- All tables of Key Results component



The command line start allows to fully automate parameter variations with **greenius**. You just need a tool which can execute commands in command line and modify the input ASCII files. For example this is possible with Matlab®.

Known Issues/Errors and Workarounds

Error Message „ Could not find the IAPWS Libraries "

Since Version 3.3 **greenius** offers the additional fluid *WaterIAPWS* for parabolic trough fields. In contrast to the fluid *Water* this enables the simulation of direct steam generation in parabolic trough collector fields.

The fluid properties of water and steam are calculated using third party software tools since the calculation of water/steam properties with the required accuracy and in a manner that the function values and their first derivatives are continuous requires some effort. Therefore **greenius** uses commercial water/steam tables for this task. If water/steam tables are not installed on your system, you may not use this optional fluid in **greenius**.

Currently **greenius** is prepared to use water/steam tables from 2 different commercial sources:

Extended IAPWS-IF97 Steam Tables

W. Wagner and U. Overhoff, CD-ROM Edition, ISBN 3-540-21412-7

If you have got a license of this software, you should copy the following files to your **greenius** directory: `IF97BO.DLL`, `DFORRT.DLL`, and `DLLPRGRS.DLL`. They can be found in the subdirectory `DLL` of the installation medium.
Further information about this software is given here: [Chair of Thermodynamics - Software for the Industrial Formulation IAPWS-IF97 for Water and Steam]()

Or:

WinSteam

WinSteam is a product of Techware Engineering Applications, Inc., 130 Skyline Drive, #194, Ringwood, NJ 07456.

A 30-day evaluation version of the software can be downloaded from http://www.techwareeng.com/

If you have got WinSteam, you should check whether the DLL `TSteam32.dll` is present either in your **greenius** directory (the directory of the greenius.exe) or in the C:\WINDOWS\system32 directory. If not, it should be copied to your **greenius** directory.

Due to licence respectively compatibility issues, the only open source alternative implemented is CoolProp:

CoolProp

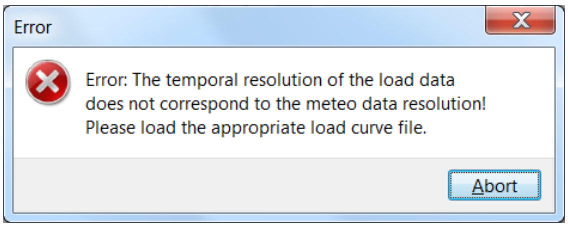
CoolProp is an open access C++ library for the calculation of properties of numerous fluids: http://www.coolprop.org

You may also find more information on CoolProp in this publication:

Ian H. Bell, Jorrit Wronski, Sylvain Quoilin and Vincent Lemort: *Pure and Pseudo-pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp*, Industrial & Engineering Chemistry Research, Volume 53, Number 6, Pages 2498 - 2508, 2014, http://pubs.acs.org/doi/abs/10.1021/ie4033999

Please note that the **CoolProp library is not recommended for the usage with greenius** even though it is possible. The fluid property calculation for the water/steam is very slow compared to the commercial alternatives. This has a massive impact on the simulation performance (DSG process heat simulation requires 2-3 hours with hourly resolution). If you still want to use the CoolProp library the easiest way is to download the shared library binaries from SourceForge: http://sourceforge.net/projects/coolprop/ Go to the `shared_library` folder of the latest version and make sure to download the Windows version of `CoolProp.dll` for `32bit_stdcall` calling convention. Finally, copy the DLL to the **greenius** directory (containing also greenius.exe).

Error Message „The temporal resolution of the load data does not correspond to the meteo data resolution“



If you get to see this message, the reason might be that you have loaded a meteorological data file with a finer resolution than 1 hour (e.g. 10 min or 15 min) and tried to run the simulation. **greenius** takes the temporal resolution of the meteo data file as time step for the simulation. Even if you want to simulate the “solar only” mode, **greenius** needs a Load Curve component. This is normally created automatically for hourly time steps and the user must not define a load curve or operation strategy. This automatic generation of a “solar only” load curve is not implemented for smaller time steps than one hour, but the user must load an appropriate “Solar Only XXmin.gpa” explicitly. They are delivered together with your **greenius** version.

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Further Information and Contact

Please contact the **greenius** developer team using ***freegreenius@dlr.de*** if you have any issues with the software.

Feedback, bug reports and ideas for new features are always welcome.

You may also get further Information about **greenius** from

Deutsches Zentrum für Luft- und Raumfahrt e.V.

Solarforschung

Dr.-Ing. Jürgen Dersch

51170 Köln

Email: juergen.dersch@dlr.de