SFERA-III

Solar Facilities for the European Research Area

1st Summer School “Thermal energy storage systems, solar fields and new cycles for future CSP plants”
WP1 Capacity building and training activities
Odeillo, France, September 9th-11th 2019

Hybrid CSP – PV Plants

Examples and simulations using greenius

Daniel Benitez, DLR

NETWORKING

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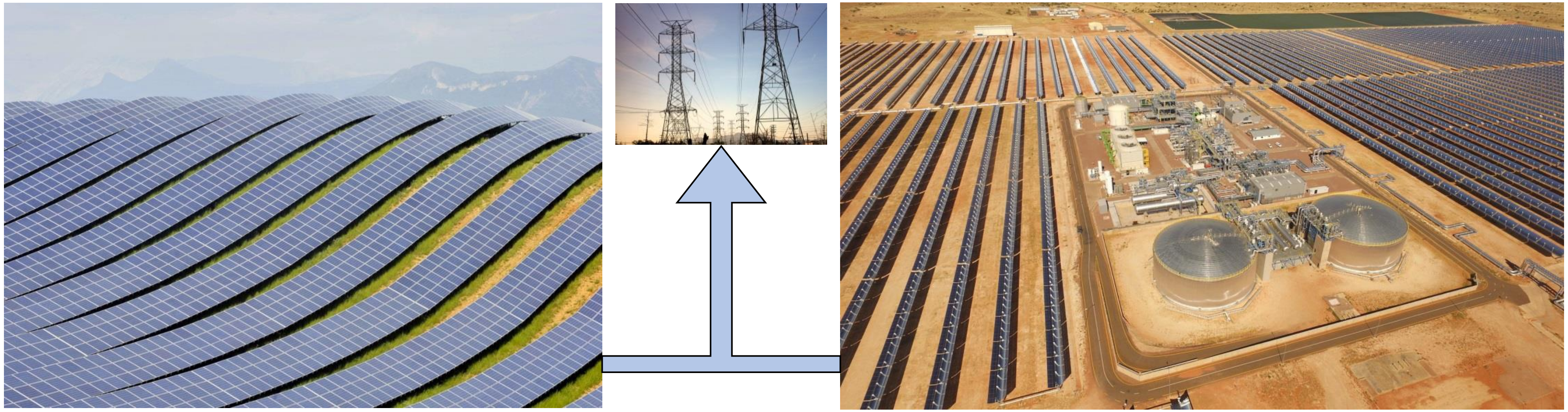
Content

16:30 – 16:40	Concepts and examples about hybrid CSP-PV plants
16:40 – 16:50	General introduction on the greenius software
16: 50 – 17:20	Setting up a simulation of a hybrid power plant with solar tower, fossil back-up and PV
17:20 – 17:30	Questions and discussions

What are hybrid CSP – PV plants?

Decoupled non-compact (or co-located) PV-CSP hybrid: independent CSP and PV plants integrated together by the electric power dispatching and management system

Energy coupled PV-CSP hybrid: Via PV-topping technology, spectral beam splitting (SBS) technology or their combination. *New Trend: PV power in CSP plant's thermal energy storage?*



PV plant. Source: www.zdnet.com

Bokpoort CSP Plant (Sener). Source: www.solarpaces.org

Why hybrid CSP – PV plants?

For solar systems, **PV offers the lowest Levelized Cost of Electricity** (LCOE) of around **3 cent€/kWh**
Storage system (batteries) for commercial PV plants are **too expensive** (400 – 600 €/kWh$_e$)
CSP integrates **low cost energy storage** for a total LCOE of around **7 cent€/kWh** (about 20 - 35 €/kWh$_{th}$ for the storage)
⇨ **The hybridization** of both technologies **combines their main advantages**:

Low investment cost of PV + cheap storage capability of CSP
= 24/7 power at an "average" LCOE around 5 cent€/kWh

PV plant. Source: www.zdnet.com

Bokpoort CSP Plant (Sener). Source: www.solarpaces.org

Cost data based on NOOR Energy 1 plant (Dubai). Source: http://newenergyupdate.com/csp-today/acwa-power-adds-250-mw-pv-dubai-csp-project-stirling-csp-developer-lists-nasdaq-small-caps

Why hybrid CSP – PV plants?

Key Features of PV plants:

- Low investment costs
- Low site preparation required
- Low Operation & Maintenance efforts
- Very low water consumption
- Expensive energy storage = unstable electricity generation

Key Features of CSP plants:

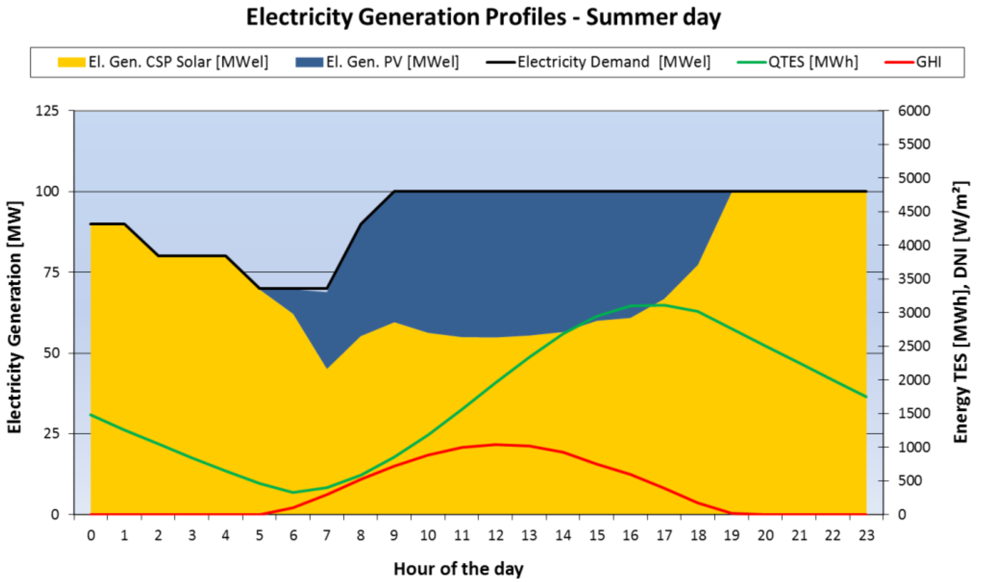
- More difficult site selection & preparation
- Use of Direct Normal Irradiance (DNI)
- Operation & Maintenance efforts similar to a conventional power plant
- Medium to high water consumption
- Cheap energy storage = base load electricity generation

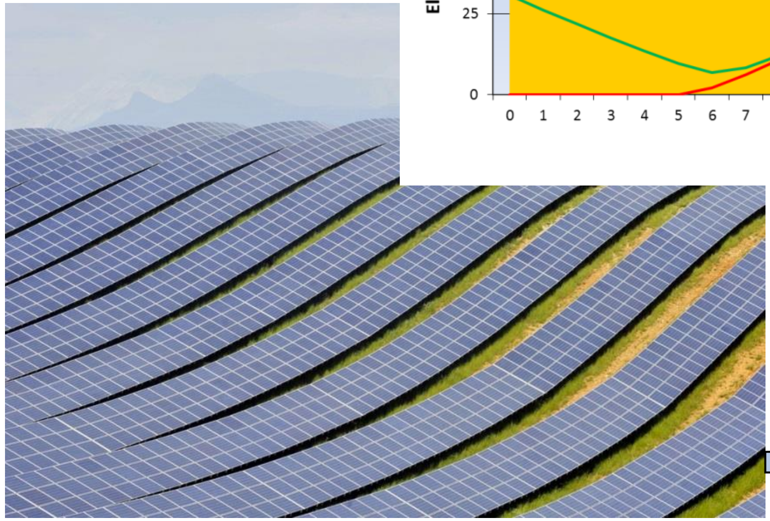
PV plant. Source: www.zdnet.com

Bokpoort CSP Plant (Sener). Source: www.solarpaces.org

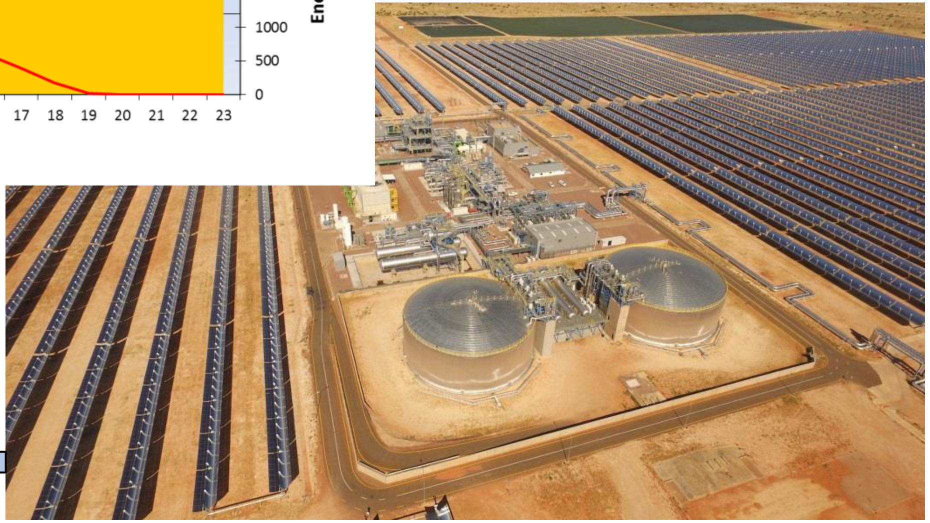
Cost data based on NOOR Energy 1 plant (Dubai). Source: http://newenergyupdate.com/csp-today/acwa-power-adds-250-mw-pv-dubai-csp-project-stirling-csp-developer-lists-nasdaq-small-caps

Why hybrid CSP – PV plants?





PV plant. Source: www.zdnet.com



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Examples of Hybrid CSP – PV plants

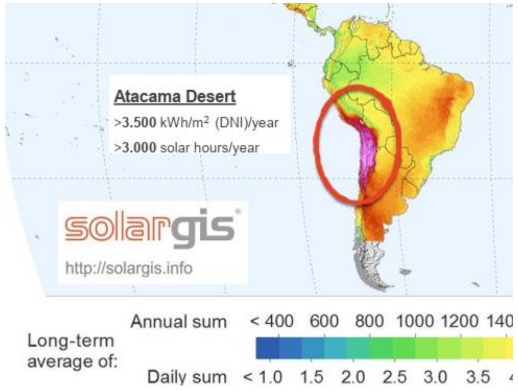
Plant name: Cerro Dominador (previously Atacama-1)
Location: Calama, Chile

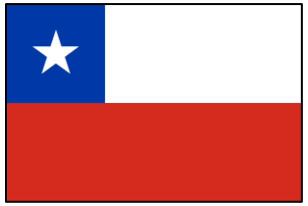
CSP capacity: 110 MW (net)
Storage capacity: 17,5 hours (2-tanks molten salt)
Number of heliostats: 10.600
Tower height: 250 m

PV capacity: 100 MW

Total electrical power capacity: 210 MW

Current status: under construction
(~80% completion by July 2019)





https://www.evwind.es/2019/07/22/first-concentrated-solar-power-plant-in-chile-and-latin-america-has-80-progress/68142

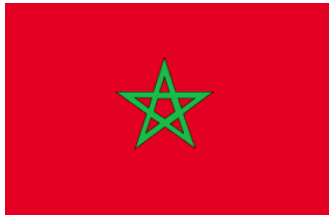
Plant name: NOOR Middelt
Location: Middelt, Morocco

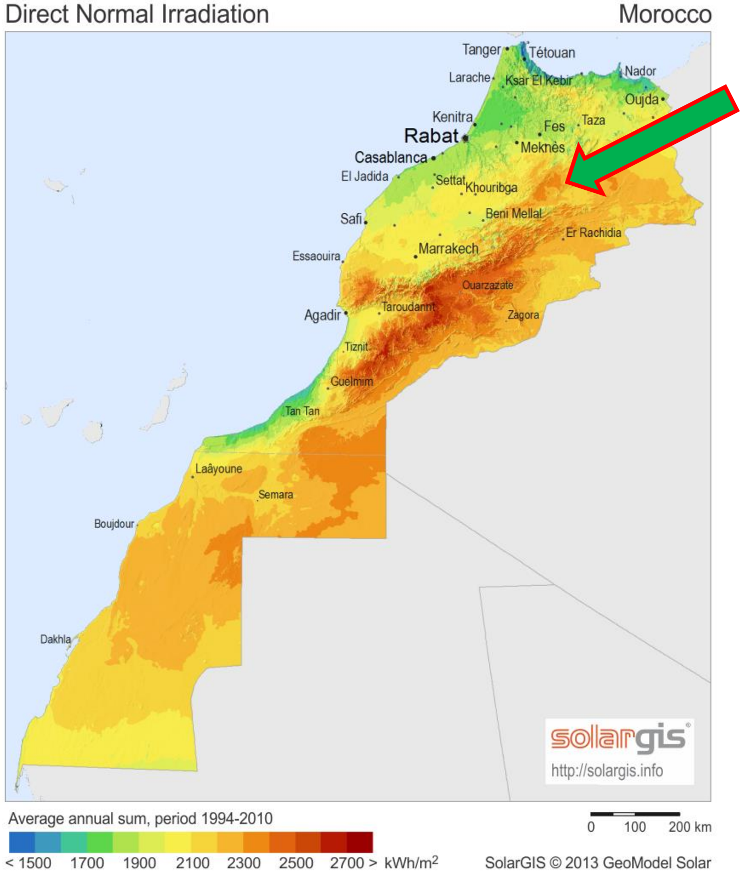
CSP capacity: 2 x 150 to 190 MW
Storage capacity: TBD, minimum 5 hours
CSP technology: TBD, probably parabolic troughs

PV capacity: 2 x 210 to 250 MW

Total electrical power capacity: 2 x 400 = 800 MW
Record lowest LCOE: 7 $cent / kWh

Current status: Consortium selected (EDF EN 35%, Masdar 30%, Green of Africa 10%, and 25% by MASEN), next financial steps ongoing.





Plant name: Noor Energy 1
Location: Dubai

CSP capacity: 700 MW
Storage capacity: 15 hours
CSP technology: parabolic trough 3 x 200 MW
tower system 1 x 100 Mwe
Tower height: 260 m

PV capacity: 250 MW

Total park power capacity: 950 MW
PPA of 7,3 cent$/kWh (35 years)

Current status: under construction
(completion expected end 2022)

https://www.evwind.es/2019/07/22/first-concentrated-solar-power-plant-in-chile-and-latin-america-has-80-progress/68142

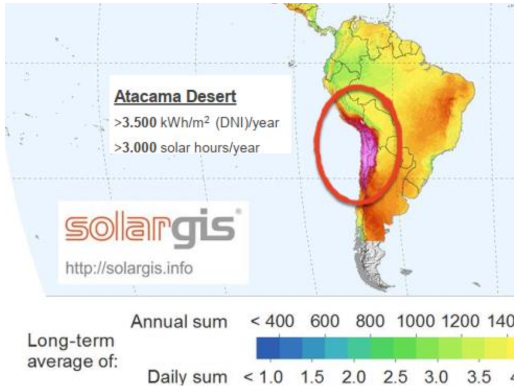
Plant name: Distrito Tecnológico Solar Diego de Almagro
Location: Diego de Almagro, Chile

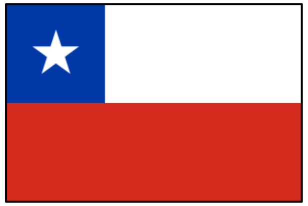
CSP capacity: 6 x 110 MW (net)
Storage capacity: about 12 hours
Tower height: about 220 m

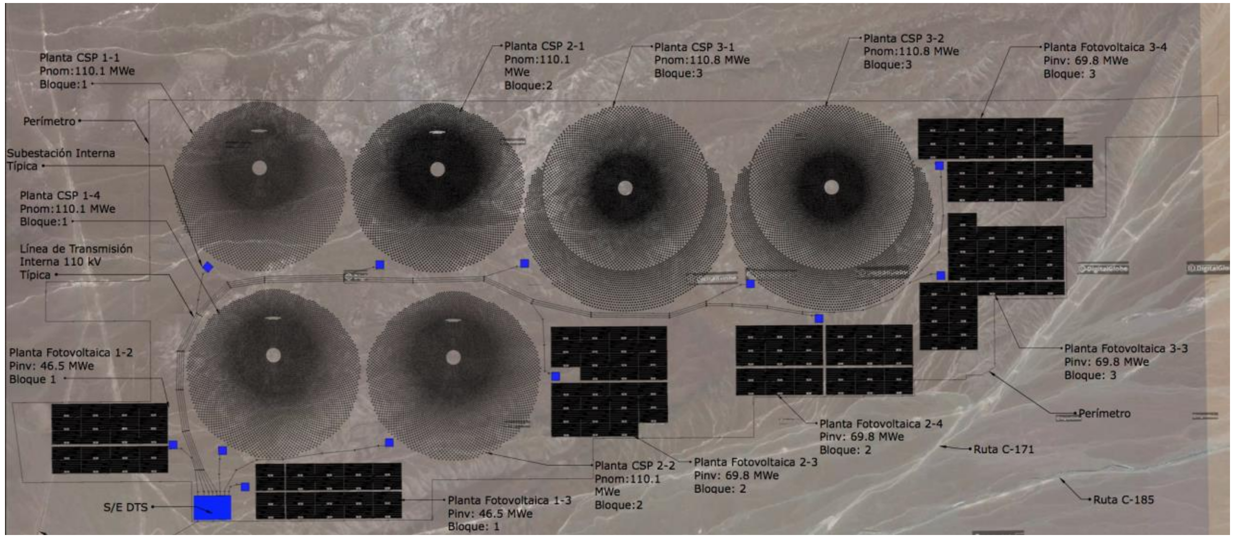
PV capacity: 6 x 50 MW

Total electrical power capacity: about 900 MW

Current status: under project development





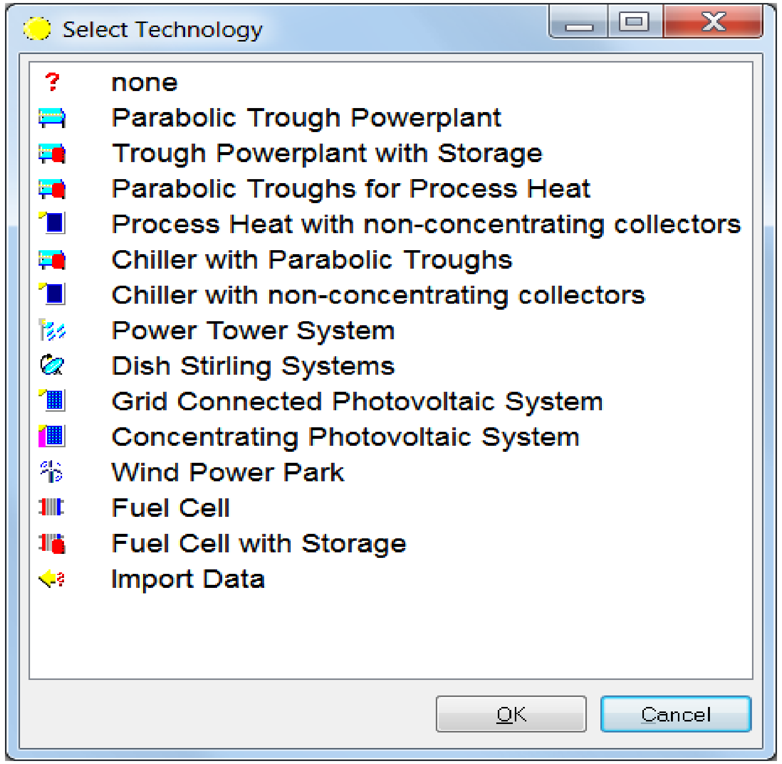


Simulation of Hybrid CSP – PV plants

greenius
THE GREEN ENERGY SYSTEM ANALYSIS TOOL

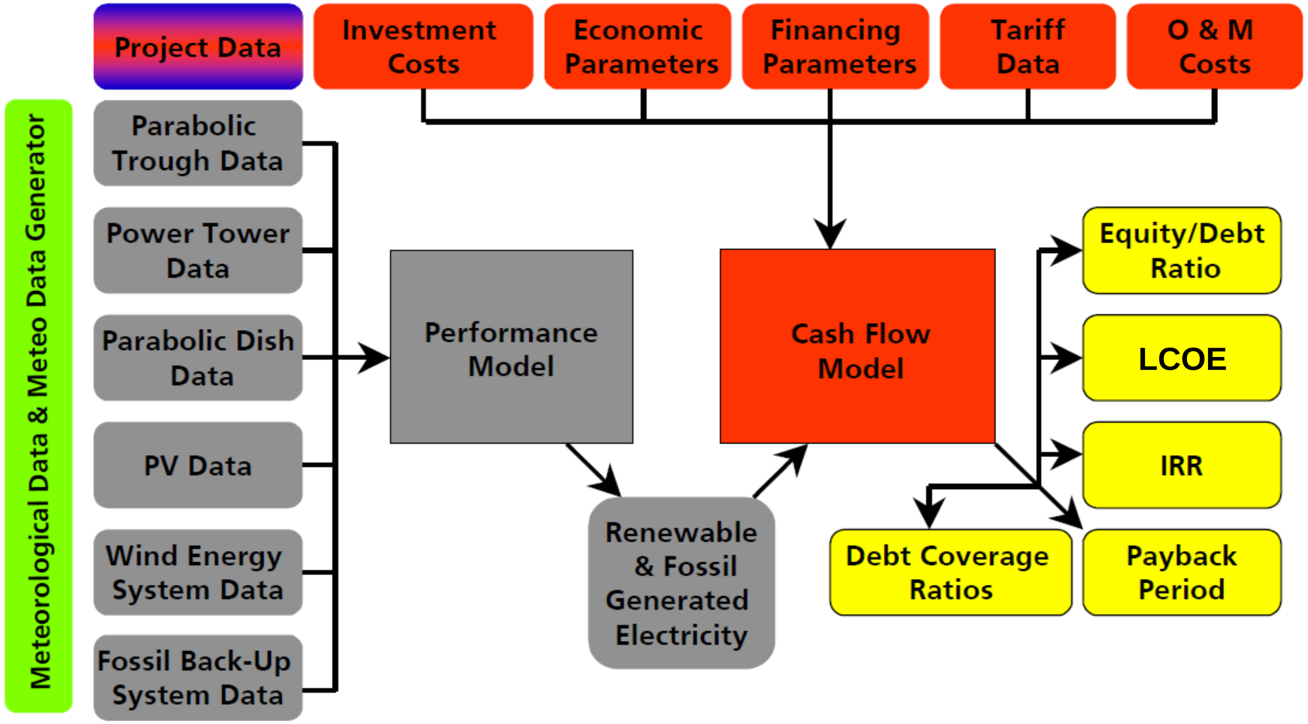
The software tool greenius

- Free of charge & easy to install
- Simulation of different renewable energy systems for heat or electricity generation
- Main focus on concentrating solar technology
- Customized for fast and simple calculations
- Based on hourly performance simulation of a typical year (min. time step length 10min)
- Utilization for feasibility studies, technology comparisons, etc.
- User support by DLR



Homepage of **greenius**:
http://freegreenius.dlr.de/

General purpose of greenius



Independent simulation of power plants

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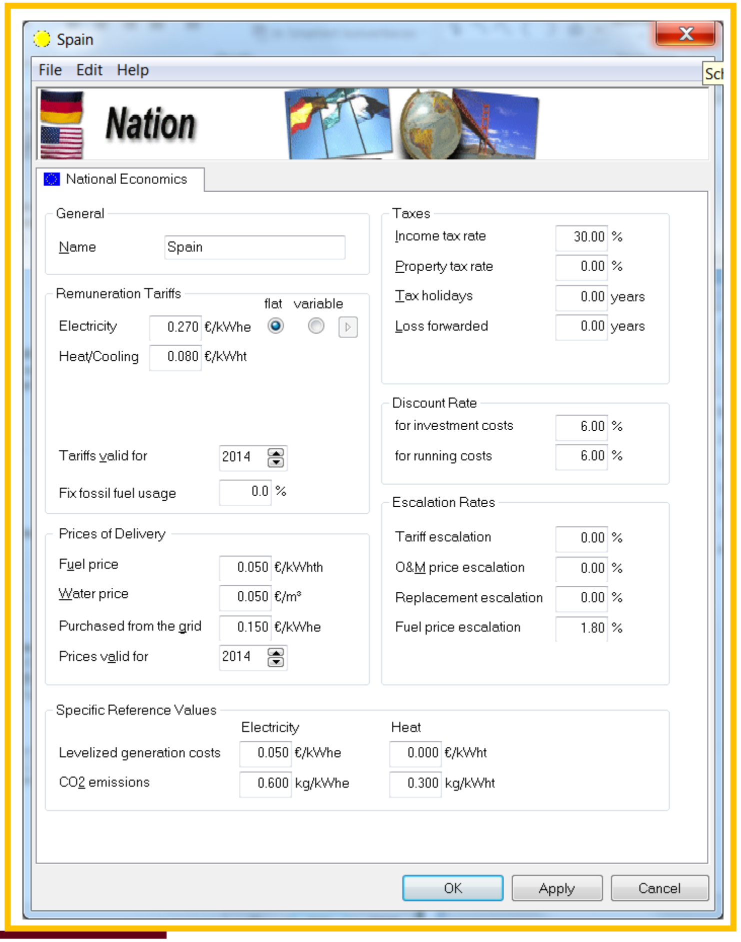
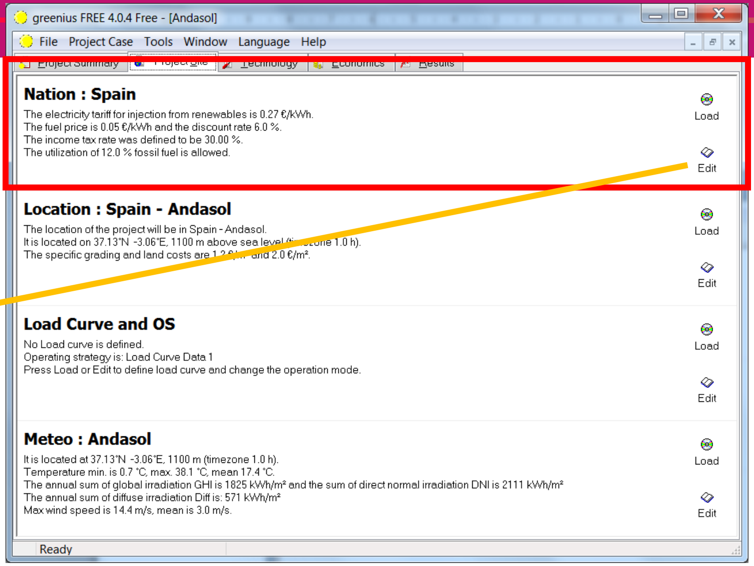
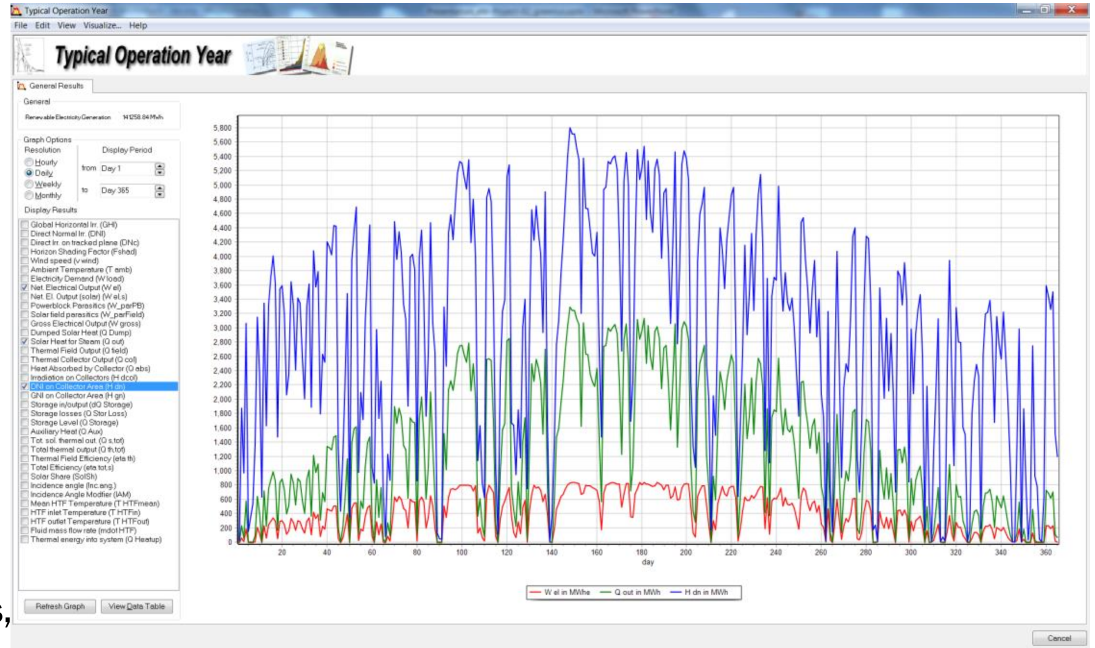
greenius graphical user Interface





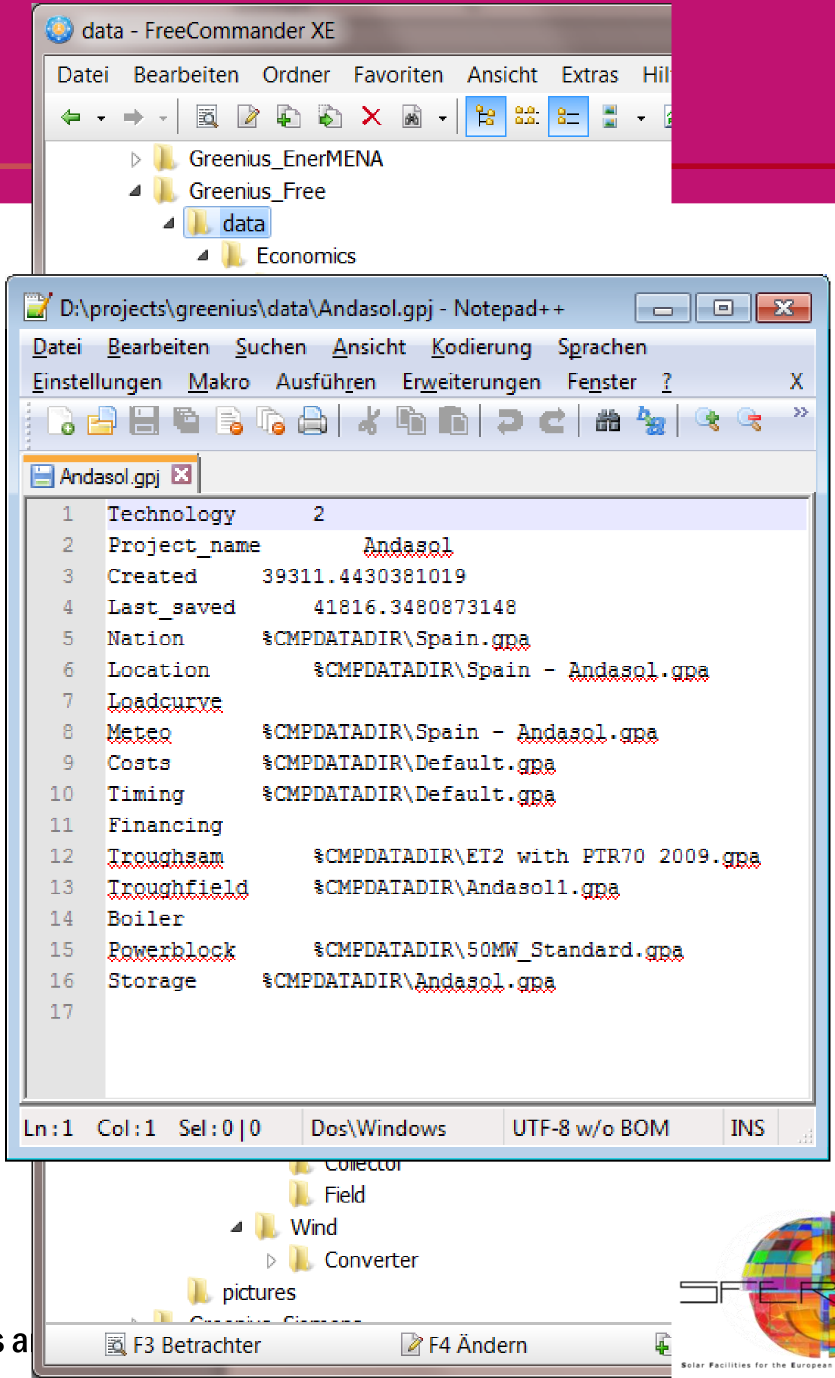
Inputs

Outputs:



Structure of the greenius directory

Several installations of greenius may exist on local drive
The greenius root directory contains the executable and required DLLs
The data directory contains all datasets, those installed with greenius as well as those generated and saved by you
Sub-directories under „data“ are named according to the equivalent component/form
greenius projects are saved as *.gpj files, default directory is the „data“ directory
These *.gpj files contain only names of *.gpa- files which have to be used for the project
All *.gpa and *.gpj files are ASCII files and may be viewed by a text editor
For exchange of whole projects, greenius offers the „export“ and „import“ functions



Component file structure in greenius

- All component files are found under

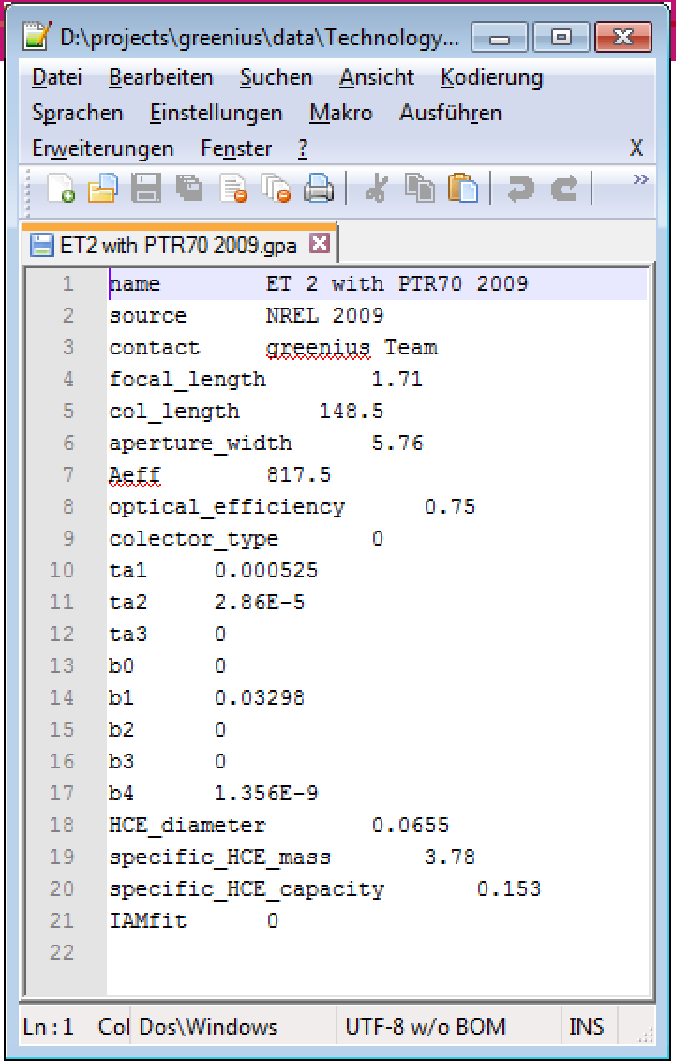
  `...\Greenius-Directory\data\...`

- Each Component type has its own subdirectory

- Content in form:
  Parameter <TAB> Value

- Commas and points are both interpreted as decimal markers

- NO separators for thousands allowed

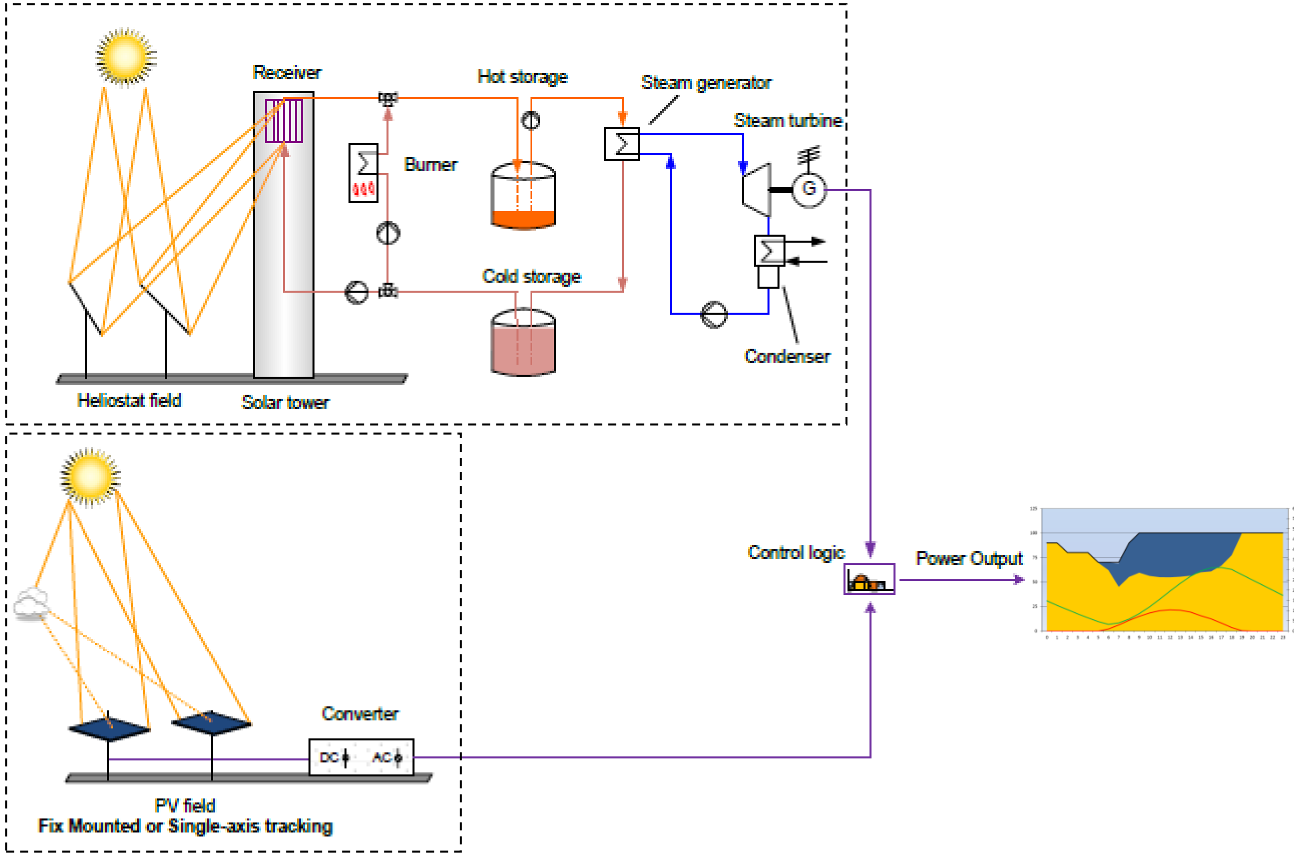



```
name	ET 2 with PTR70 2009
source	NREL 2009
contact	greenius Team
focal_length	1.71
col_length	148.5
aperture_width	5.76
Aeff	817.5
optical_efficiency	0.75
colector_type	0
ta1	0.000525
ta2	2.86E-5
ta3	0
b0	0
b1	0.03298
b2	0
b3	0
b4	1.356E-9
HCE_diameter	0.0655
specific_HCE_mass	3.78
specific_HCE_capacity	0.153
IAMfit	0
```

Example project in greenius:

Simulation of a Hybrid
Solar Tower CSP + PV plant

Technology Configuration



Source:
Crescent Dunes power plant: www.solarreserve.com
https://www.nextracker.com/product-services/solar-storage/truecapture/

Main Steps

1. Select **plant configuration**: overall plant nominal net electrical power, technology types, PV capacity, CSP solar multiple, thermal storage size, back-up thermal power, etc.

Design Paramenters		
Overall Plant Net Output	MWel	100.0
CSP: Solar Tower with Molten Salt and TES		
Nominal Capacity	MWel	112.0
Solar Multiple	-	2.4
Thermal Storage Capacity	h	12.0
Auxiliary HTF Heater	MWt	254.0
PV: Polycrystalline 1-axis tracked		
Nominal Capacity (DC)	MWp	142.2
Inverter Capacity	MWp	123.1
Battery Capacity	h	0.0

Main Steps

2. Create a data book with the required input parameters and performance characterization: component types (module & inverter, CSP collector, turbine, back-up heater, etc.), efficiency curves, auxiliary consumptions, heat losses, etc.

→ greenius has examples, but it is not a component-design software!

Parameters PV & Inverter fixed			ALL COUNTRIES
No.	Item	Unit	2015
parameter 1	PV Manufacturer	-	JA Solar
parameter 2	PV Module Type	-	JAP6 72-320/3BB
parameter 3	Tracking y/n	-	y
parameter 4	Nominal Module Power	W	380
parameter 5	Nominal Module Efficiency	%	19.6
parameter 6	Number of serial modules	-	20
parameter 7	Number of parallel module strings	-	220
parameter 8	Number of Systems	-	100
parameter 9	Collector distance (shadowing)	m	9.50
parameter 10	Inverter Manufacturer	-	SMA
parameter 11	Inverter Type	-	SunnyCentral CP1000-XT **
parameter 12	Nominal Inverter Power	kW	1,190
parameter 13	Nominal Inverter DC Voltage	V	688
parameter 14	Inverter design efficiency	%	98.7
parameter 15	Wiring losses at full power (STC), AC+DC	%	1.44
parameter 16	Module quality + module array losses	%	1.1
parameter 17	Other losses (soiling?)	%	2
parameter 18	PV / Battery config (AC or DC)	-	AC
parameter 19	Availability	%	98
parameter 20	Degradation	%/y	0.5

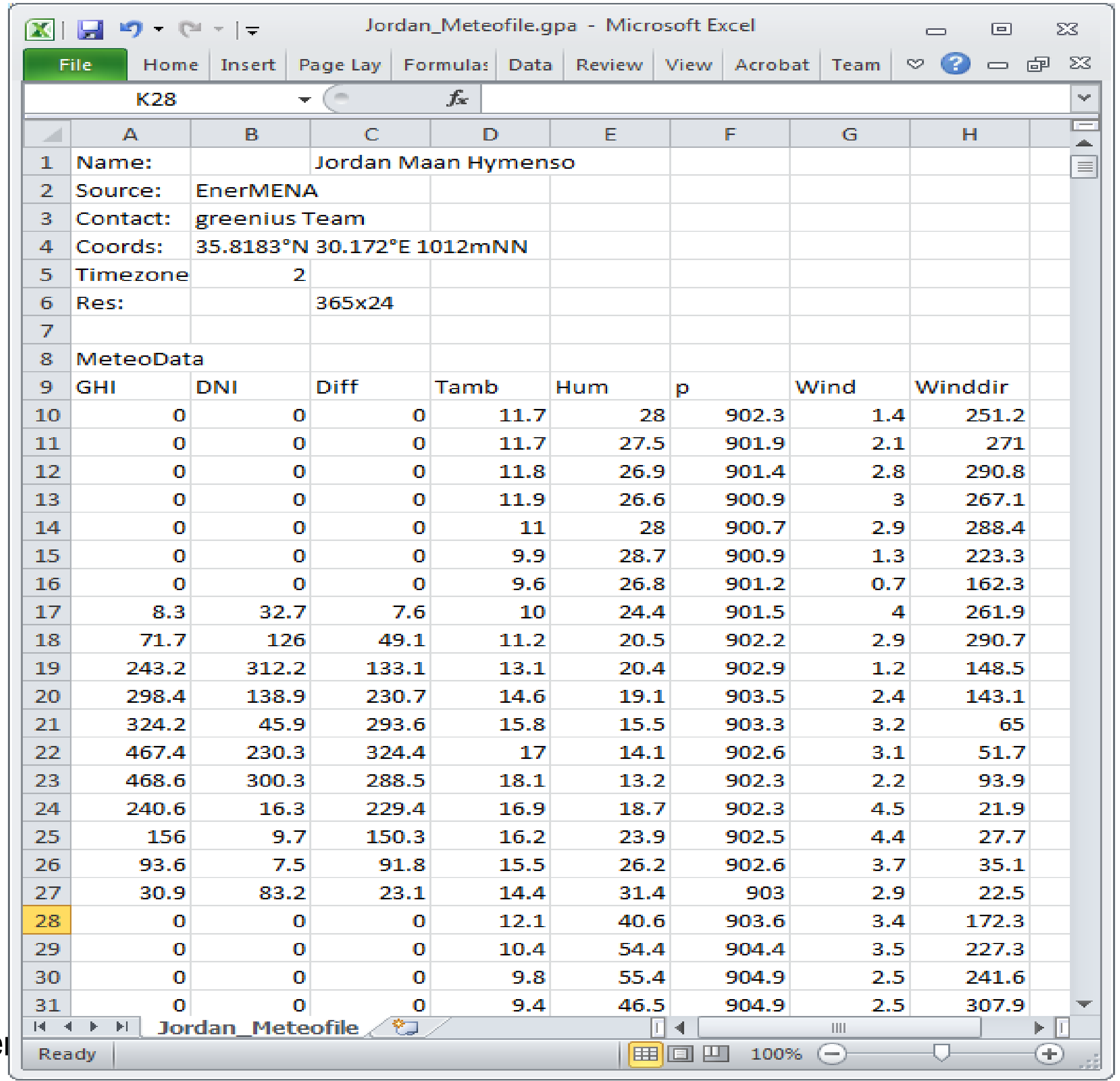
No.	Item	unit	Value
a.	**Heliostat**		
1.	Heliostat type/name	[-]	Multi-facetted glass metal heliostat with 2-axes drive, pedestal mounted
	Net reflective area per heliostat	[m²]	121
	Aperture width	[m]	12.93
	Aperture height	[m]	9.57
	Number of facets	[-]	28 (4x7)
	Annual mean reflectivity	[%]	95 x 97 x 99 = 91.23
	Beam error	[mrad]	3.50
	Canting	[-]	On-axis
	Parasitic consumption	[kW_{el}]	-
b.	**Solar field – system definition**		
	Field layout	[-]	Surround
	Solar Multiple	[-]	2.4
	Number of heliostats	[-]	8860
	Net field reflective area	[m²]	1,072,060
	Optical efficiency of solar field @ DP	[%]	68.5
	Total land area	[m²]	5,407,294

f.	Power block general		
	Design net electrical Power	[MW_{el}]	100
	Design gross electrical Power	[MW_{el}]	112.1
	Design gross efficiency	[%]	42.82
	Design net efficiency	[%]	38.20
	Cooling type	[-]	ACC
	Design condenser conditions	[mbar / °C]	155 / 54
	Minimum / maximum thermal load	[%]	20 / 100

Main Steps

3. Local data preparation – Meteofile

   a) Obtain the measured meteorological data: ground based or satellite derived
   b) Open an existing meteofile from greenius in excel
   c) Change the information according to the new file: name, location, coordinates, timezone, resolution and meteodata (keep the header labels!)
   d) Save as text-file (*.txt) in your software folder, e.g. D:\greenius\Greenius\data\Site\Meteo
   e) Rename the file extension to *.gpa

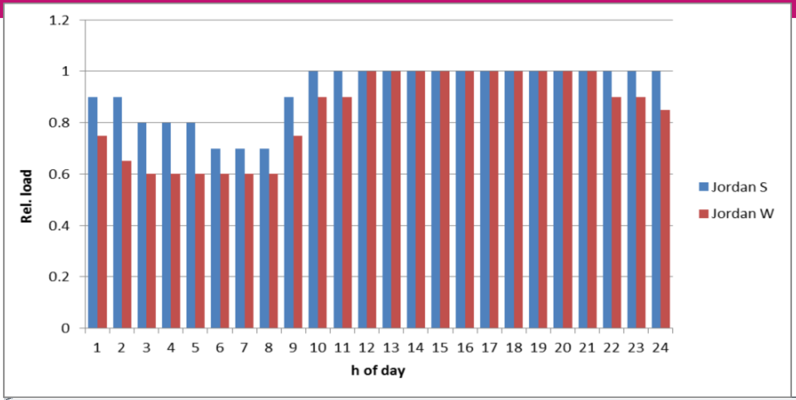

Jordan_Meteofile.gpa - Microsoft Excel

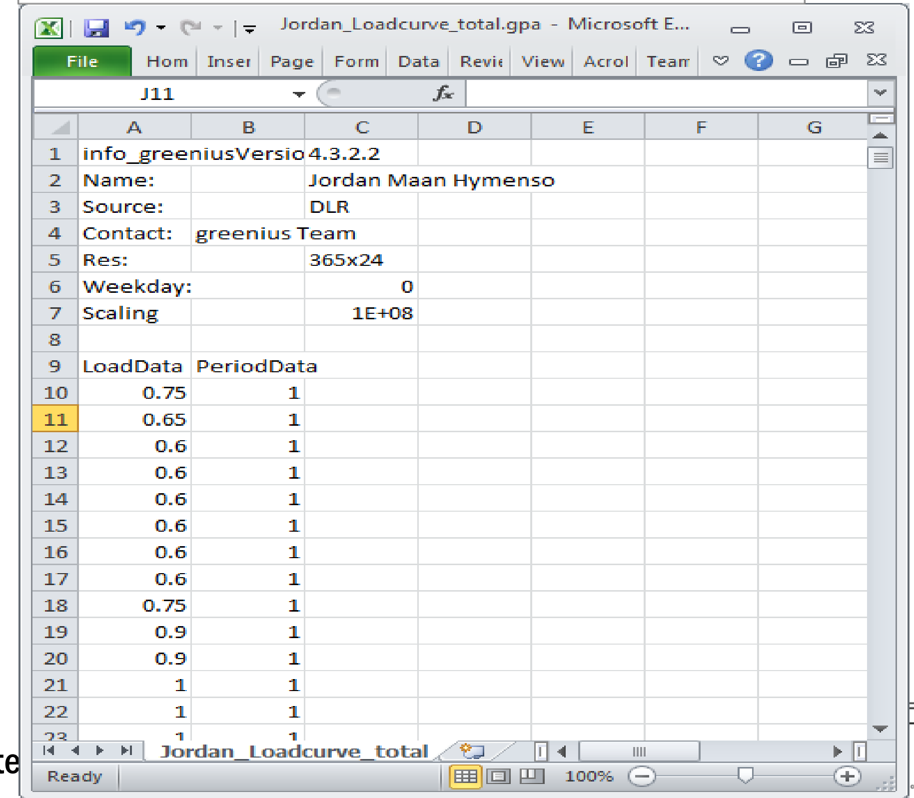
	A	B	C	D	E	F	G	H
1	Name:		Jordan Maan Hymenso					
2	Source:	EnerMENA						
3	Contact:	greenius Team						
4	Coords:	35.8183°N 30.172°E 1012mNN						
5	Timezone	2						
6	Res:		365x24					
7								
8	MeteoData							
9	GHI	DNI	Diff	Tamb	Hum	p	Wind	Winddir
10	0	0	0	11.7	28	902.3	1.4	251.2
11	0	0	0	11.7	27.5	901.9	2.1	271
12	0	0	0	11.8	26.9	901.4	2.8	290.8
13	0	0	0	11.9	26.6	900.9	3	267.1
14	0	0	0	11	28	900.7	2.9	288.4
15	0	0	0	9.9	28.7	900.9	1.3	223.3
16	0	0	0	9.6	26.8	901.2	0.7	162.3
17	8.3	32.7	7.6	10	24.4	901.5	4	261.9
18	71.7	126	49.1	11.2	20.5	902.2	2.9	290.7
19	243.2	312.2	133.1	13.1	20.4	902.9	1.2	148.5
20	298.4	138.9	230.7	14.6	19.1	903.5	2.4	143.1
21	324.2	45.9	293.6	15.8	15.5	903.3	3.2	65
22	467.4	230.3	324.4	17	14.1	902.6	3.1	51.7
23	468.6	300.3	288.5	18.1	13.2	902.3	2.2	93.9
24	240.6	16.3	229.4	16.9	18.7	902.3	4.5	21.9
25	156	9.7	150.3	16.2	23.9	902.5	4.4	27.7
26	93.6	7.5	91.8	15.5	26.2	902.6	3.7	35.1
27	30.9	83.2	23.1	14.4	31.4	903	2.9	22.5
28	0	0	0	12.1	40.6	903.6	3.4	172.3
29	0	0	0	10.4	54.4	904.4	3.5	227.3
30	0	0	0	9.8	55.4	904.9	2.5	241.6
31	0	0	0	9.4	46.5	904.9	2.5	307.9

Main Steps

3. Local data preparation – Load Curve (total)

a) Obtain the load curve data: electrical demand for the complete power plant
b) Open an existing load file from greenius in excel
c) Change the information according to the new file: name, resolution and scaling factor (nominal output in W) and load relative to maximum load
d) Save as text-file (*.txt) in your software folder, e.g. D:\greenius\Greenius\data\Site\Loadcurve
e) Rename the file extension to *.gpa

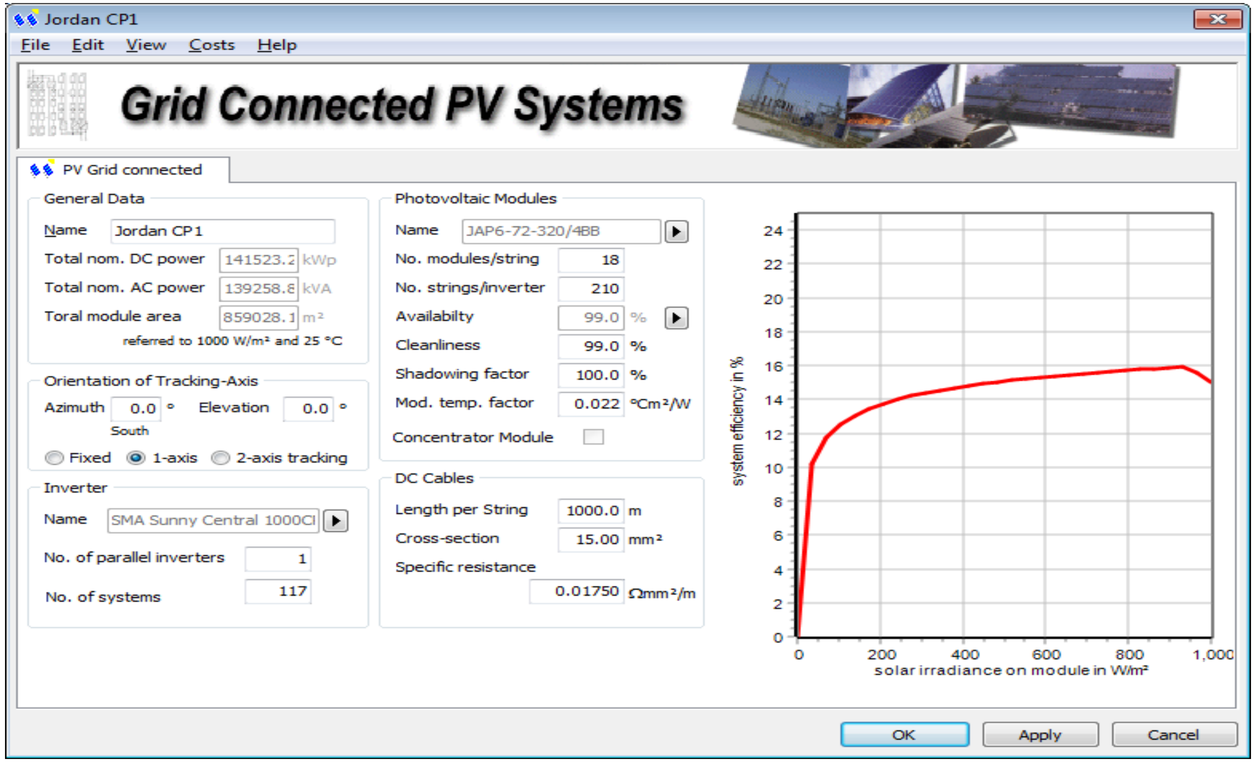


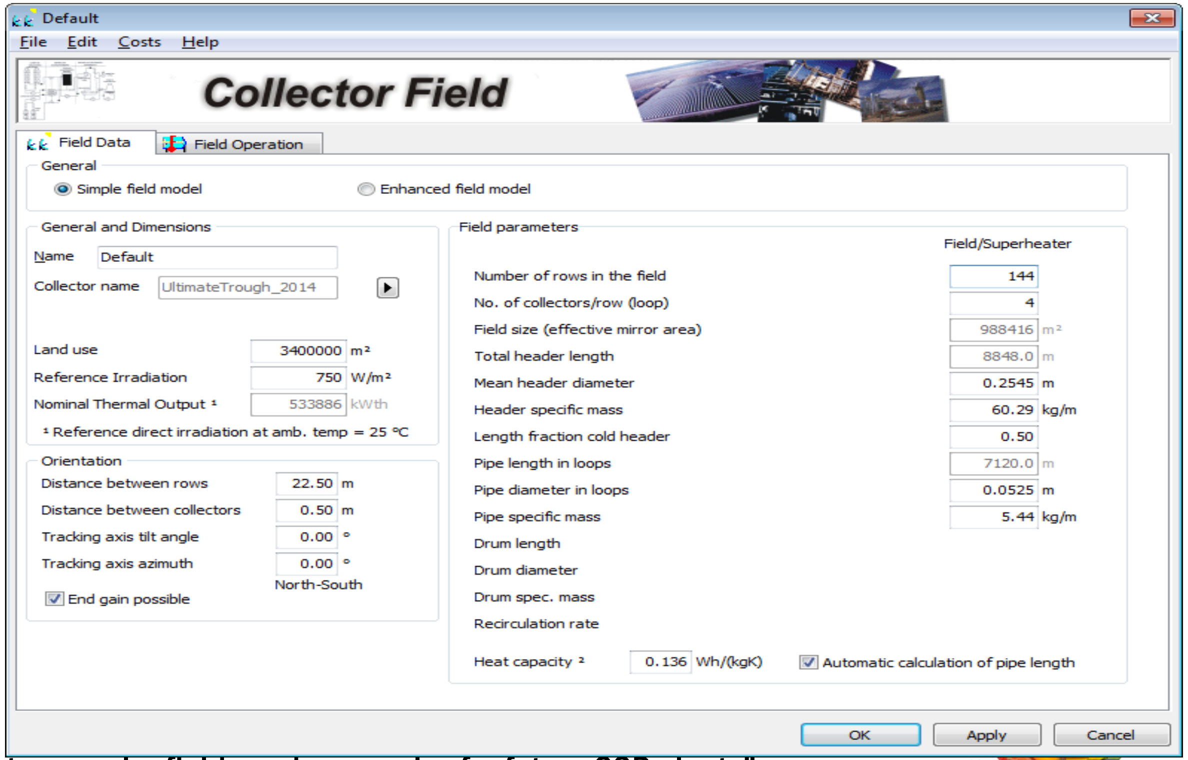


	A	B	C	D
1	info_greeniusVersio		4.3.2.2	
2	Name:		Jordan Maan Hymenso	
3	Source:		DLR	
4	Contact:	greenius Team		
5	Res:		365x24	
6	Weekday:		0	
7	Scaling		1E+08	
8				
9	LoadData	PeriodData		
10	0.75	1		
11	0.65	1		
12	0.6	1		
13	0.6	1		
14	0.6	1		
15	0.6	1		
16	0.6	1		
17	0.6	1		
18	0.75	1		
19	0.9	1		
20	0.9	1		
21	1	1		
22	1	1		
23	1	1		

Main Steps

4. Determine **cost factors**: fuel cost, land cost, equipment CAPEX & OPEX, financing parameters, etc.
5. Create a **new project** in greenius and **adjust the parameters**.





Main Steps

6. For the case of hybrid CSP-PV plant:

   a) First simulate the **PV plant** with the **total load curve**

   b) Determine the **rest load** not covered with the PV plant

   c) Then simulate the CSP plant with **new load curve** based on rest load

   d) Combine "manually" the results of PV and CSP to obtain the **total yield** and **overall LCOE**.

See now example in greenius and MS Excel

Steps for combining PV and CSP results

Rest load not covered with the PV plant:

1. Copy all the hourly results of PV into excel sheet
2. Determine residual load in MW: difference Wload – W ToGrid

New load curve for CSP:

1. Set values of residual load > 0 and < minimum load to minimum load
2. Calculate relative load (0 to 1) as residual load / nominal load
3. Generate gpa-file as shown on slide 19 above

Calculate CSP plant with new load curve (if allowed, use fossil fuel under "Load Curve / Operation Strategy / "Gas support up to" = 1)

Steps for combining PV and CSP results

Merge CSP and PV results (total net electrical output):

1. Sum net electrical output of both plants ("Wnet" PV + "W el" CSP)
2. Calculate corrected PV to grid. Demand cannot be exceed although CSP is forced to run at minimum load, therefore PV output must be reduced.
3. Calculate final sum of net electrical output

Determine if part of the **offline auxiliary consumption of CSP plant** can be covered with **excess generation from PV**:

1. Calculate generation above demand
2. Determine original offline auxiliary consumption of CSP
3. Calculate adjusted offline auxiliary consumption of CSP after using excess energy from PV. Energy to be taken from electrical grid.
4. Calculate new reduced PV curtailment (for information only)

Steps for combining PV and CSP results

Calculate combined LCOE for hybrid plant

1. Write down the LCOE and net electrical output of PV calculated by greenius

2. Calculate new LCOE of PV adjusted with reduced electricity production (due to minimum load limitation of CSP):

$$LCOE_{PV\ new} = \frac{E_{net\ PV\ original}}{E_{net\ PV\ new}} * \ LCOE_{PV\ original}$$

3. Write down the LCOE and net electrical output of CSP calculated by greenius
4. Calculate the average of the LCOE of PV and CSP weighted with the electricity generation:

$$LCOE_{hybrid} = \frac{LCOE_{PV\ new} * E_{net\ PV\ new} + LCOE_{CPS} * E_{net\ CSP}}{E_{net\ PV\ new} + E_{net\ CSP}}$$

THANK YOU

for your attention!

THANKS to my colleagues

for their work and input