IEESL Industrial, Energy and Environmental Systems Lab

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Evaluation of environmental and economic feasibility of Renewable Energy systems; a stochastic Life Cycle Assessment and Cost analysis approach

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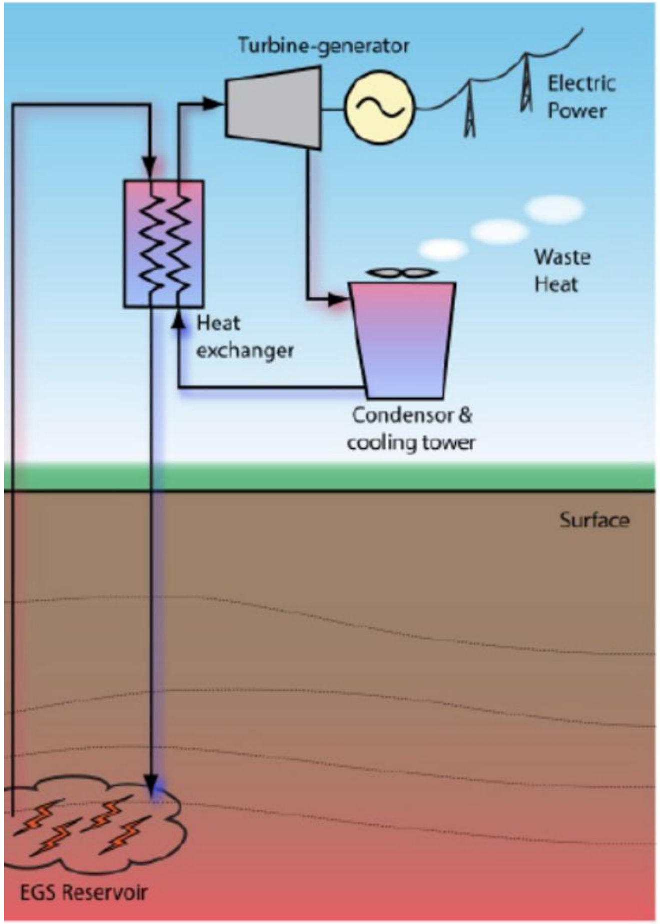
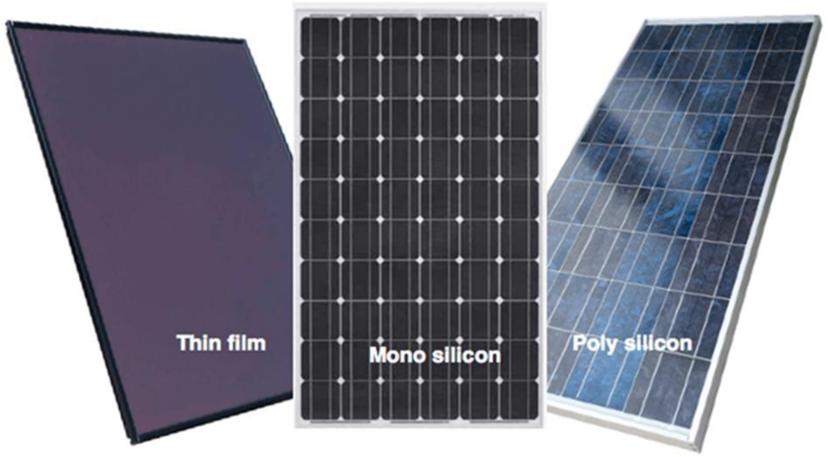
Geothermal power plants



Parameter	Medium capacity	Low capacity
Net plant power [MW_{el}]	5.5	2.9
Well depth [km]	5	5
Number of wells	6 (2 well triplets)	3 (1 well triplet)
Surface plant life time [years]	30	20
Reservoir temperature [°C]	190	165
Annual net energy generation [GWh yr^{-1}]	46	24
Total energy produced [GWh]	7524	3308
Plant cost [€/kW_{el} installed]	4900	

- The two HDR systems modelled vary in capacity of the geothermal source: medium and low (5.5 and 2.9 MW_{el} respectively).
- One of the boreholes is used as the injection well for the cold fluid leaving the generation unit, the other two as production wells, which provide the hot fluid, heated up within the hot rock formation.

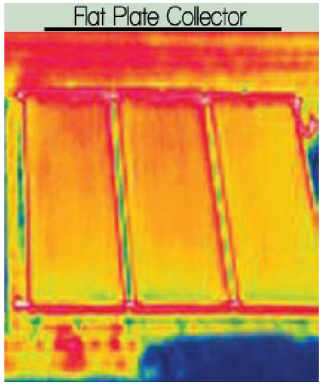
Photovoltaic systems

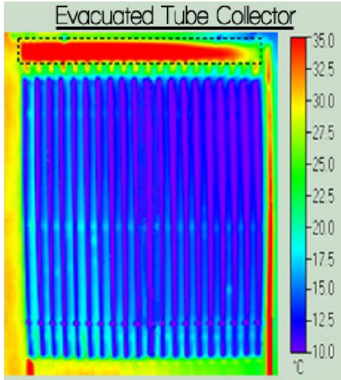


	PV technology	Cell efficiency [%]	Frame area [m²]	Capacity per unit [W]	Total area [m²]
Crystalline	sc-Si	17	1.18	200	17.7
	mc-Si	12.3	1.02	125	24.5
Thin-film	CIS	10.6	0.94	100	28.2
	a-Si	6.1	0.82	50	49.2

	Photovoltaic technology	Technical characteristics
Crystalline technologies	**Single crystalline silicon cells (sc-Si)**	The active material is made from a single crystal without grain boundaries. The sc-Si cells have the highest efficiencies (for commercial cells: 13-18%).
	Multi-crystalline silicon cells (mc-Si)	The cell material consists of different crystals. The cells have a lower efficiency, but it is cheaper in production. Commercial mc-Si cells have efficiencies in the range of 11-16%.
Thin-Film Technologies	**Copper-indium-diselenide (CIS)**	CIS modules are constructed by depositing extremely thin layers of photovoltaic materials on a low cost layer (such as glass, stainless steel or plastic). Material costs are lower because less semi-conductor material is required; secondly, labor costs are reduced because the thin films are produced as large, complete modules and not as individual cells that have to be mounted in frames and wired together. The efficiency is about 8-11%.
	Amorphous cells (a-Si)	A new developed thin-film technology is hydrogenated amorphous silicon. The efficiency of amorphous cells is about 6-9% and decreases during the first hundred operation hours.

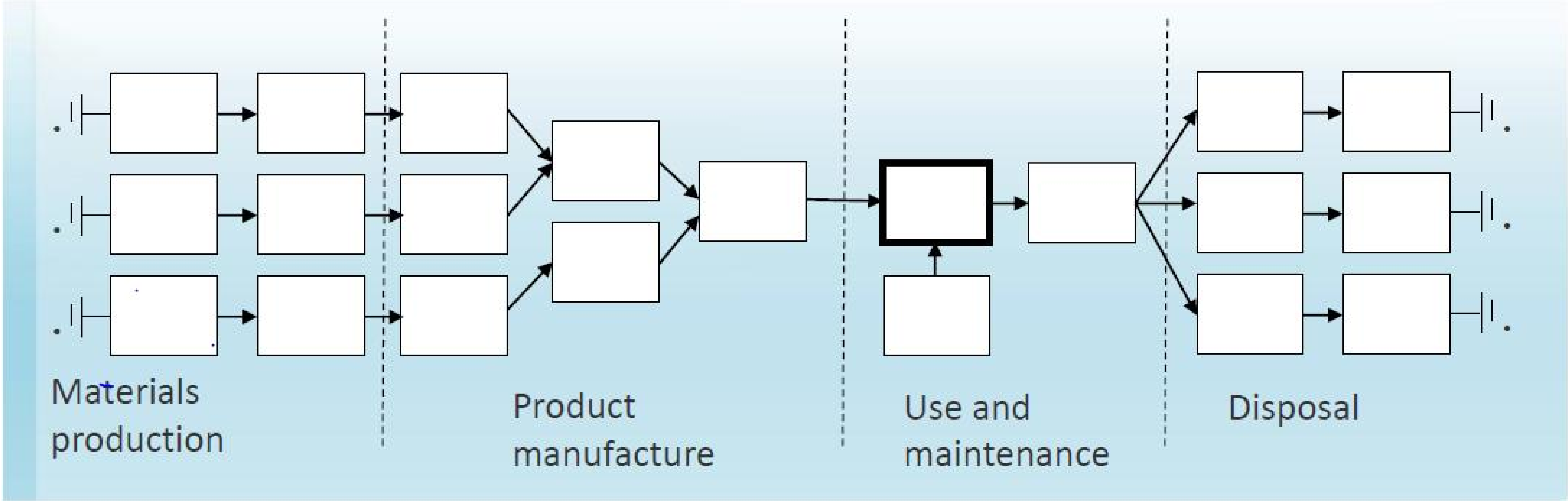
Solar thermal systems





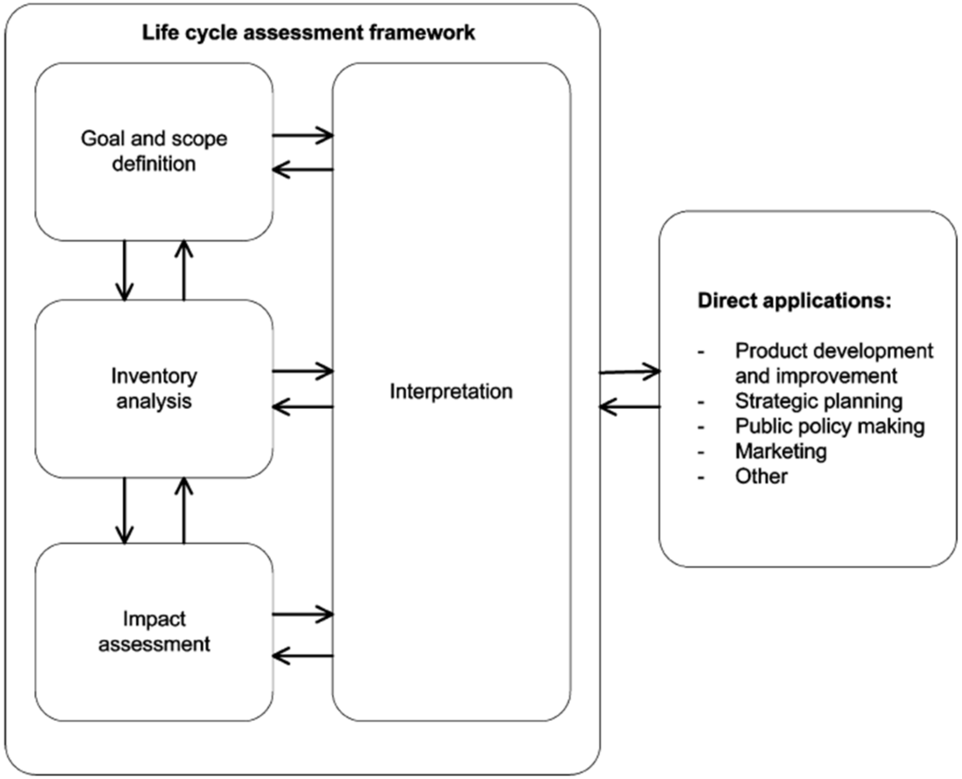
- ⇨ The flat solar collector consists of the dark absorber, the transparent cover, the heat transfer fluid containing the antifreeze and the water tank.
- ⇨ Heat transfer fluid circulates through tubes contained in the absorber. They are usually made of copper or aluminum and are painted with a special selective coating, which is much better in absorbing and retaining heat than ordinary colors.
- ⇨ The vacuum tube collector is more efficient and cost-effective than the flat collector: ~ 70% performance (compared to ~ 50%) and cost almost 1.5 times higher.
- ⇨ It consists of vacuum tubes of glass containing copper tubes in their center. The fluid circulated in the collector tube is heated and then sent through the pipes into the water tank.
- ⇨ Vacuum tubes are easier to install because they are lightweight, compact and can be transported to the roof individually. In addition, the pipes can be replaced separately if they are damaged, avoiding the need to replace the entire collector.
- ⇨ Both types of collectors are effective and durable with a life span of over twenty years.

Life Cycle Assessment



- A leading **environmental** assessment methodology, which studies the environmental aspects and potential impacts throughout a product's life cycle (Cradle-to-Grave or Cradle-to-Cradle) from raw materials extraction through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences.
- A **standardized** methodology (ISO 14040 & ISO 14044).
- Comparative assessment.

Methodological stages of LCA



Goal and scope definition. During the first step the goal and scope of the study are defined as well as the selection of the functional unit (FU) and the system's boundaries.

Inventory analysis (LCI). In the second step, a life cycle inventory analysis, of relevant energy and material inputs and environmental releases, is made up identifying and quantifying inputs and outputs at every stage of the life cycle.

Impact assessment (LCIA). LCIA translates emissions and resource extractions into a limited number of environmental impact scores by means of characterization factors, in two ways i.e. at midpoint and at endpoint level. Midpoint indicators focus on single environmental problems, e.g. climate change. Endpoint indicators show the environmental impact on three higher aggregation levels: 1) human health, 2) biodiversity and 3) resource scarcity.

Interpretation. The results of the LCI and LCIA are interpreted and combined to make a more informative and sound decision. A sensitivity analysis is performed to validate the consistency of the results.

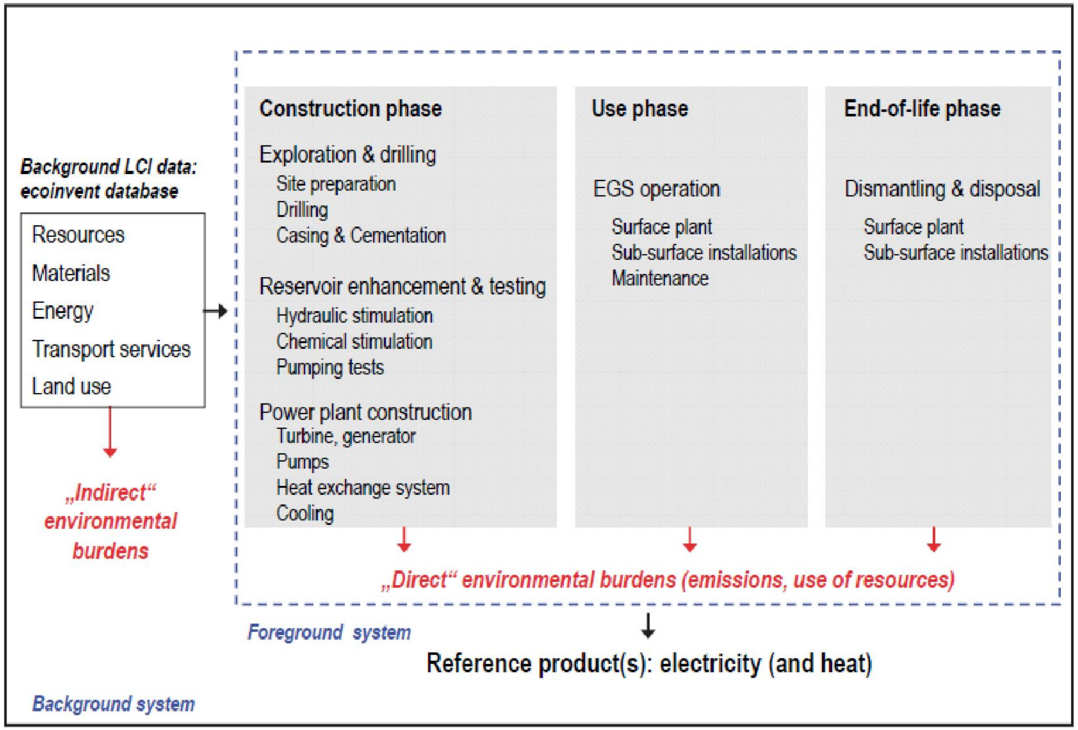
Uncertainty in LCA

- As outlined by ISO 14040 series standards, any life cycle assessment requires a number of phases for its integration. Each of these phases, along with their associated databases and models, has significant associated uncertainties. A variety of specific uncertainty sources are listed below:
- **Database uncertainty**. Defined as the error introduced on the outcome due to variability on measurements, lack of data, and deficient model assumptions. Normally, input output uncertainty data cannot be derived from available information, as there is commonly one source of information which gives average values without any data about uncertainty.
- **Model uncertainty.** Simplified models may have uncertainties that could affect the quality of the assessment outputs. Moreover, they may not capture exact cause-and-effect mechanisms, or data regression may have the wrong functional form. There may be unknown interactions among model parameters.
- **Statistical/measurement error.** Estimating distributions of properties from a limited set of sample data creates statistical variability. The sample data may also have measurement errors, or the standards used to collect and quantify the data may not be known.

One of the several methods that propagate uncertainties is Monte Carlo simulation. This method makes use of an algorithm capable of producing a series of random numbers, within the uncertainty value of every input and output taken into account in the scenarios created, for which it assumes a lognormal distribution, with a confidence interval of 95%. In this study, a Monte Carlo analysis was selected as the statistical method and was performed using SimaPro 8.5 software (5000 runs) for each scenario and impact category.

Detailed results for the studied Renewable Energy Systems

System boundaries for a LCA



Background LCI data: ecoinvent database

- Resources
- Materials
- Energy
- Transport services
- Land use

„Indirect“ environmental burdens

Construction phase

Exploration & drilling
  - Site preparation
  - Drilling
  - Casing & Cementation

Reservoir enhancement & testing
  - Hydraulic stimulation
  - Chemical stimulation
  - Pumping tests

Power plant construction
  - Turbine, generator
  - Pumps
  - Heat exchange system
  - Cooling

Use phase

EGS operation
  - Surface plant
  - Sub-surface installations
  - Maintenance

End-of-life phase

Dismantling & disposal
  - Surface plant
  - Sub-surface installations

„Direct“ environmental burdens (emissions, use of resources)

Foreground system

Reference product(s): electricity (and heat)

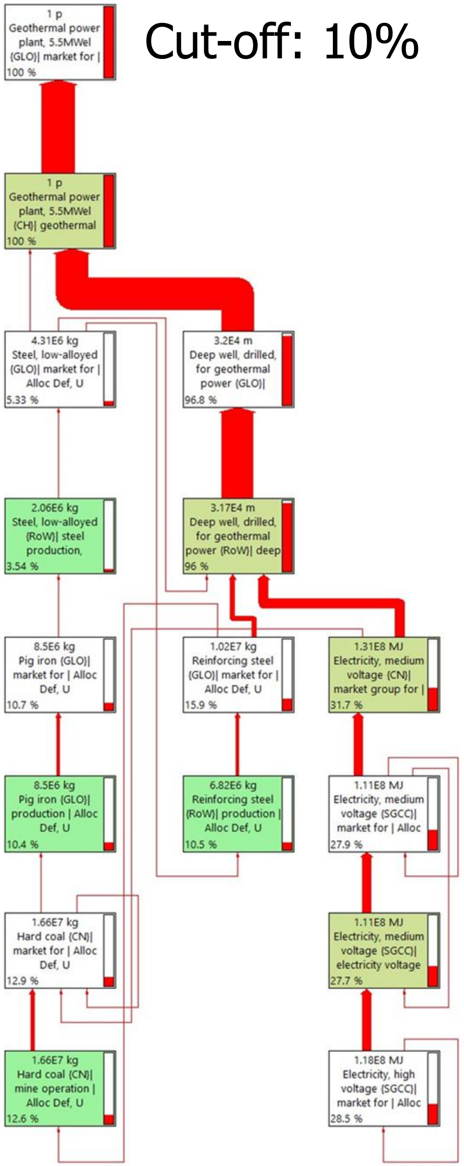
Background system

System boundaries

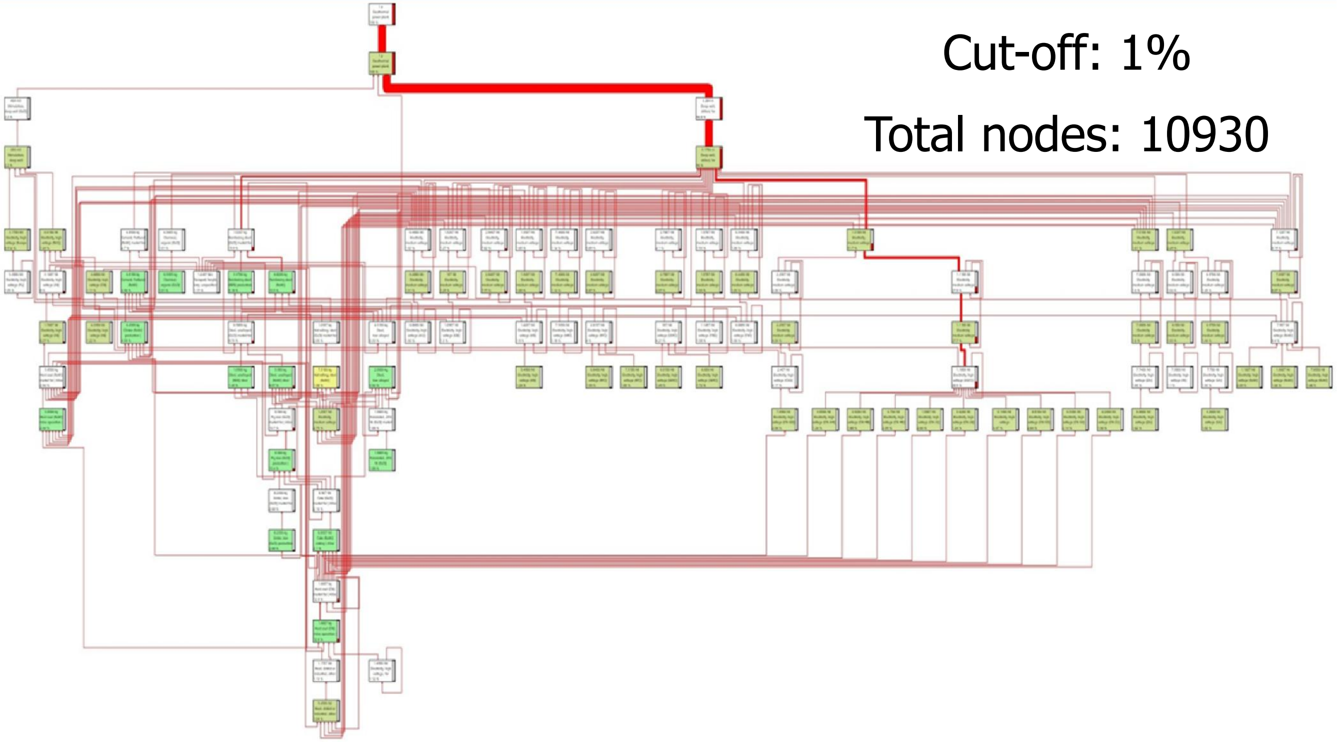
- ⇨ Goal and scope of the LCA in geothermal power plants is the quantification of environmental burdens during the complete life cycle of deep geothermal systems per unit of electricity.
- ⇨ The system can also be imagined as divided into the surface system with the power generating unit and the subsurface system with the wells, the stimulation process, and the downhole pump.
- ⇨ The functional unit of the LCA carried out is the production of 1 kWh net electricity with a deep geothermal power plant.
- ⇨ The inventory analysis accounts for all energy and material inputs, land transformation and occupation, emissions of substances to air, water and soil.

Process network

Medium capacity geothermal power plant



Cut-off: 10%

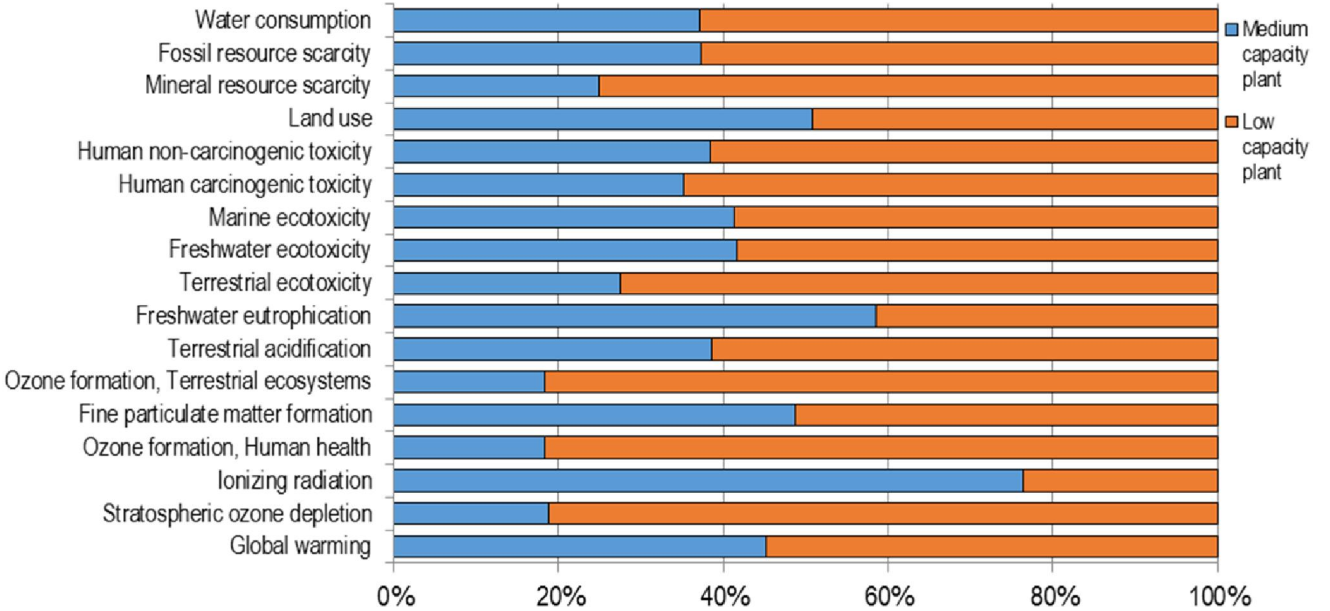


Cut-off: 1%

Total nodes: 10930

- 96.8% of all total inflows and outflows are due to the drilling of the two triplet deep well sets.
- Only 2.2% of the energy and materials inflow are due to the stimulation of the wells (requiring water and energy), the generation unit and other inputs.
- There are also impacts associated with the electricity production, transportation and system disposal.

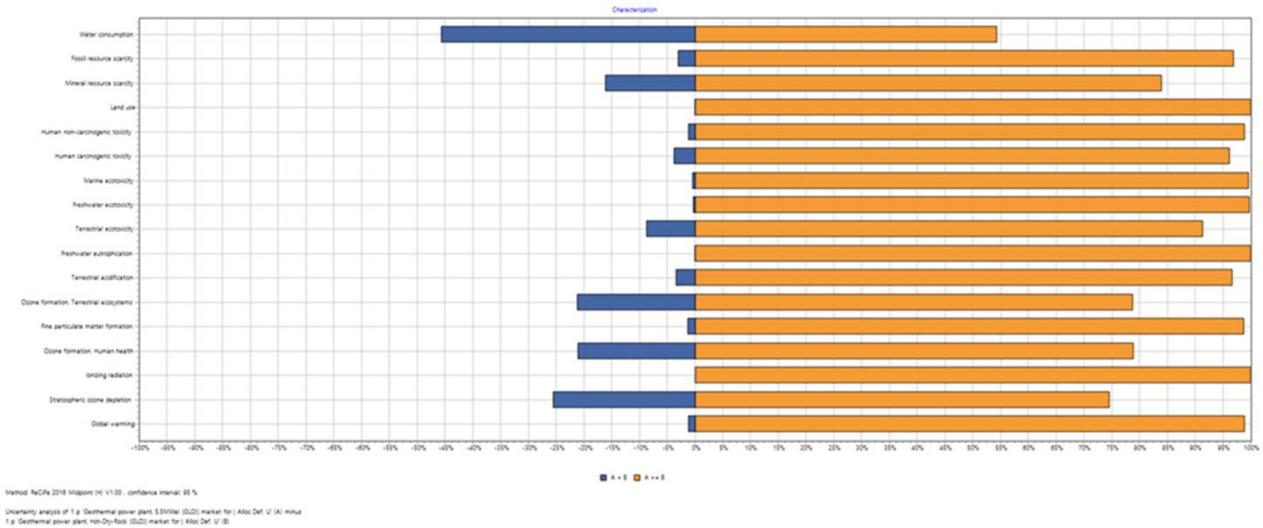
LCA results
Relative contributions to the impact categories



- ⇨ The cumulative CO_2eq emissions per kWh for each MW_e installed over the whole life cycle of the power plants vary between approximately 1.8×10^{-2} and 2.2×10^{-2} kg CO_2 eq/kWh·MW_e and the plant with the lowest capacity shows the highest impacts. This is due to the lower output of electricity over its whole life, while impacts from the dominating drilling phase are not lower for this plant.
- ⇨ For all cases the results denote that drilling phase clearly dominates the climate change impacts. The stimulation with water and energy, the generation unit and other inputs play a very minor role.
- ⇨ For the production unit, the construction of the building with the relative use of steel dominates, while the choice of fluid plays a marginal role. Energy consumption and steel use for the casing are dominated by borehole impacts.

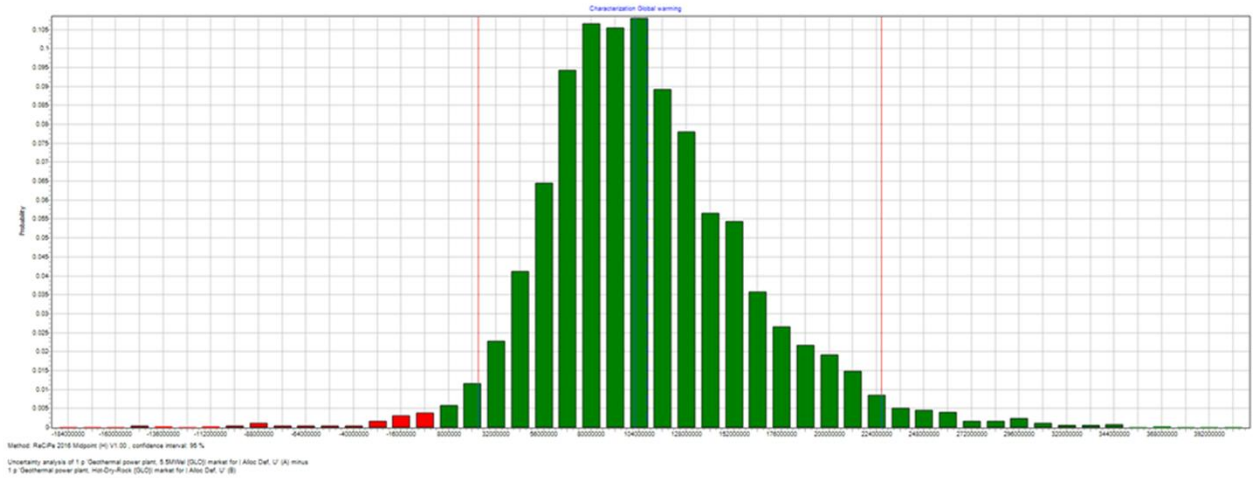
Monte-Carlo simulation results

A: medium capacity , **B:** low capacity



Method: ReCiPe 2016 Midpoint (H) V1.00 , confidence interval: 95 %

Uncertainty analysis of 1 p 'Geothermal power plant, 5.5MWel {GLO}| market for | Alloc Def, U' (A) minus
1 p 'Geothermal power plant, Hot-Dry-Rock {GLO}| market for | Alloc Def, U' (B)



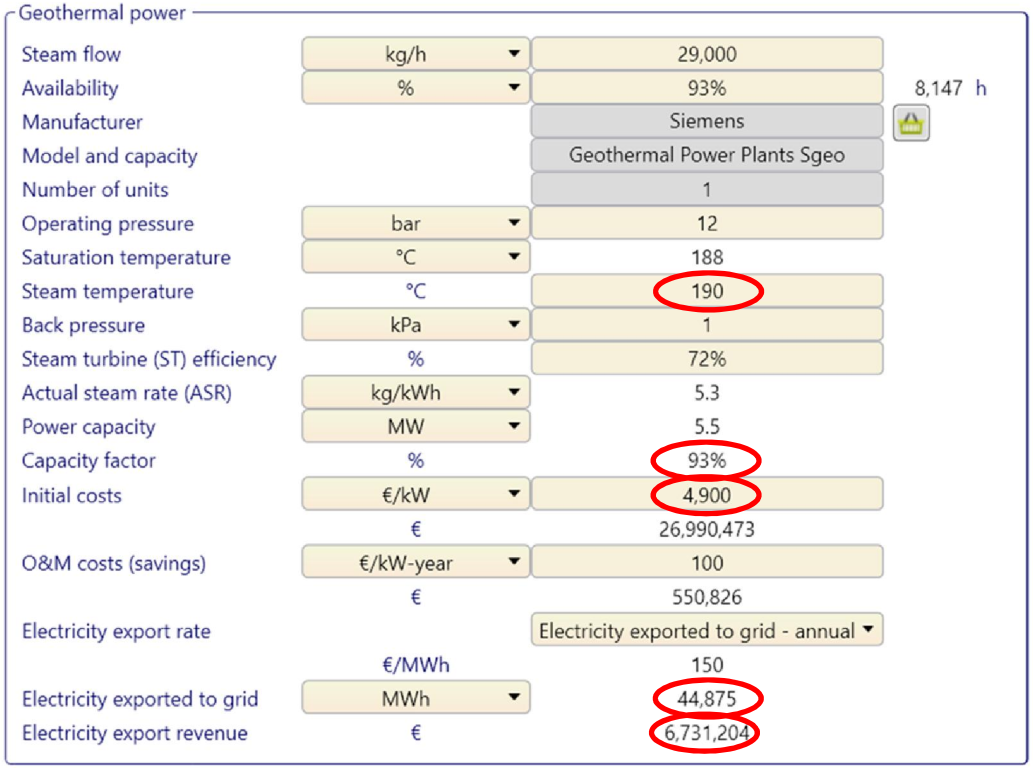
Method: ReCiPe 2016 Midpoint (H) V1.00 , confidence interval: 95 %

Uncertainty analysis of 1 p 'Geothermal power plant, 5.5MWel {GLO}| market for | Alloc Def, U' (A) minus
1 p 'Geothermal power plant, Hot-Dry-Rock {GLO}| market for | Alloc Def, U' (B)

- ⇨ Case A has increased impacts compared to case B in all midpoint categories, thus proving its improved environmental performance.
- ⇨ The above are confirmed by the histogram of the Gaussian curve for 98.8% of the 5000 cases under study.
- ⇨ This comparison refers to the LCA impacts and not to the results as previously mentioned (i.e. impacts per total grid-derived electricity and per installed capacity for each geothermal system).
- ⇨ Therefore, they do not include the 30 or 20 year generation of energy from plants, thus improving the behavior of the low-capacity geothermal plant.

Technical specifications

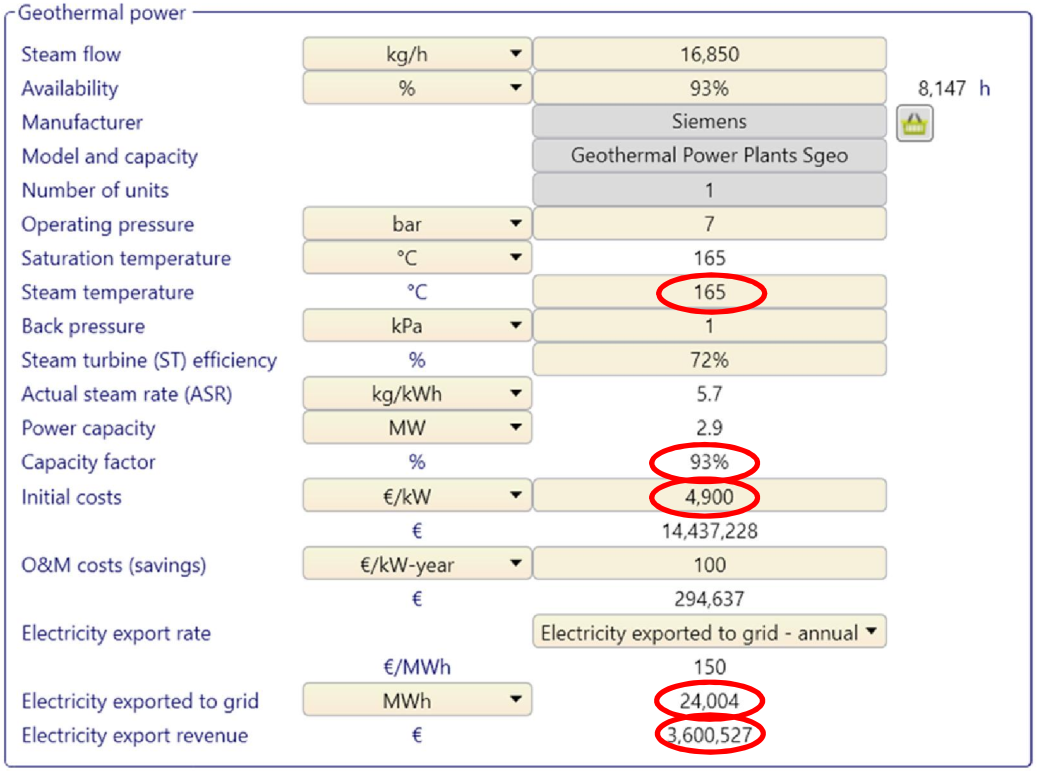
Medium capacity geothermal power plant



Geothermal power

Steam flow	kg/h	29,000	
Availability	%	93%	8,147 h
Manufacturer		Siemens	
Model and capacity		Geothermal Power Plants Sgeo	
Number of units		1	
Operating pressure	bar	12	
Saturation temperature	°C	188	
Steam temperature	°C	190	
Back pressure	kPa	1	
Steam turbine (ST) efficiency	%	72%	
Actual steam rate (ASR)	kg/kWh	5.3	
Power capacity	MW	5.5	
Capacity factor	%	93%	
Initial costs	€/kW	4,900	
	€	26,990,473	
O&M costs (savings)	€/kW-year	100	
	€	550,826	
Electricity export rate		Electricity exported to grid - annual	
	€/MWh	150	
Electricity exported to grid	MWh	44,875	
Electricity export revenue	€	6,731,204	

Low capacity geothermal power plant



Geothermal power

Steam flow	kg/h	16,850	
Availability	%	93%	8,147 h
Manufacturer		Siemens	
Model and capacity		Geothermal Power Plants Sgeo	
Number of units		1	
Operating pressure	bar	7	
Saturation temperature	°C	165	
Steam temperature	°C	165	
Back pressure	kPa	1	
Steam turbine (ST) efficiency	%	72%	
Actual steam rate (ASR)	kg/kWh	5.7	
Power capacity	MW	2.9	
Capacity factor	%	93%	
Initial costs	€/kW	4,900	
	€	14,437,228	
O&M costs (savings)	€/kW-year	100	
	€	294,637	
Electricity export rate		Electricity exported to grid - annual	
	€/MWh	150	
Electricity exported to grid	MWh	24,004	
Electricity export revenue	€	3,600,527	

- ⇨ The location of the systems was chosen to be the area of Akrotiri in Chania, assuming the existence of the necessary geothermal field as defined by the technical specifications for each installation.
- ⇨ For all economic calculations, the electricity price was set at 0.15 € / kWh (feed-in-tariff) and it was assumed that the facility was funded by itself (without a bank loan).

Financial analysis

RETScreen - Financial Analysis — **Subscriber: Viewer**

Financial parameters

General		
Inflation rate	%	2%
Discount rate	%	9%
Project life	yr	30
Finance		
Incentives and grants	€	
Debt ratio	%	0%
Income tax analysis		☐

Annual revenue

Electricity export revenue		
Electricity exported to grid	MWh ▾	44,875
Electricity export rate	€/kWh ▾	0.15
Electricity export revenue	€	6,731,204
Electricity export escalation rate	%	2%
GHG reduction revenue		
Gross GHG reduction	tCO_2/yr	32,321
Gross GHG reduction - 30 yrs	tCO_2	969,633
GHG reduction revenue	€	0
Other revenue (cost)		☐
Clean Energy (CE) production revenue		☐

Costs | Savings | Revenue

Initial costs			
Initial cost	100%	€	26,990,473
Total initial costs	**100%**	€	**26,990,473**
Annual costs and debt payments			
O&M costs (savings)		€	550,826
Total annual costs		**€**	**550,826**
Annual savings and revenue			
Electricity export revenue		€	6,731,204
Total annual savings and revenue		**€**	**6,731,204**

Financial viability

Pre-tax IRR - equity	%	25.3%
Pre-tax IRR - assets	%	25.3%
Simple payback	yr	4.4
Equity payback	yr	4.1
Net Present Value (NPV)	€	50,771,491
Annual life cycle savings	€/yr	4,941,912
Benefit-Cost (B-C) ratio		2.9
Debt service coverage		No debt
GHG reduction cost	€/tCO_2	-153
Energy production cost	€/kWh ▾	0.074

Yearly cash flows

Year \#	Pre-tax €	Cumulative €
3	6,558,666	-7,697,757
4	6,689,839	-1,007,917
5	6,823,636	5,815,719
6	6,960,109	12,775,828
7	7,099,311	19,875,139
8	7,241,297	27,116,437
9	7,386,123	34,502,560
10	7,533,846	42,036,406
11	7,684,523	49,720,929
12	7,838,213	57,559,142
13	7,994,977	65,554,119
14	8,154,877	73,708,996
15	8,317,975	82,026,971
16	8,484,334	90,511,305
17	8,654,021	99,165,325
18	8,827,101	107,992,427
19	9,003,643	116,996,070
20	9,183,716	126,179,786
21	9,367,390	135,547,176
22	9,554,738	145,101,914
23	9,745,833	154,847,747
24	9,940,750	164,788,496
25	10,139,565	174,928,061
26	10,342,356	185,270,417
27	10,549,203	195,819,620
28	10,760,187	206,579,807
29	10,975,391	217,555,198
30	11,194,899	228,750,096

Yearly cash flows

RETScreen - Financial Analysis — **Subscriber: Viewer**

Financial parameters

General		
Inflation rate	%	2%
Discount rate	%	9%
Project life	yr	20
Finance		
Incentives and grants	€	
Debt ratio	%	0%
Income tax analysis		☐

Annual revenue

Electricity export revenue		
Electricity exported to grid	MWh ▾	24,004
Electricity export rate	€/kWh ▾	0.15
Electricity export revenue	€	3,600,527
Electricity export escalation rate	%	2%
GHG reduction revenue		
Gross GHG reduction	tCO_2/yr	17,289
Gross GHG reduction - 20 yrs	tCO_2	345,772
GHG reduction revenue	€	0
Other revenue (cost)		☐
Clean Energy (CE) production revenue		☐

Costs | Savings | Revenue

Initial costs			
Initial cost	100%	€	14,437,228
Total initial costs	**100%**	€	**14,437,228**
Annual costs and debt payments			
O&M costs (savings)		€	294,637
Total annual costs		**€**	**294,637**
Annual savings and revenue			
Electricity export revenue		€	3,600,527
Total annual savings and revenue		**€**	**3,600,527**

Financial viability

Pre-tax IRR - equity	%	25%
Pre-tax IRR - assets	%	25%
Simple payback	yr	4.4
Equity payback	yr	4.1
Net Present Value (NPV)	€	20,962,157
Annual life cycle savings	€/yr	2,296,330
Benefit-Cost (B-C) ratio		2.5
Debt service coverage		No debt
GHG reduction cost	€/tCO_2	-133
Energy production cost	€/kWh ▾	0.08

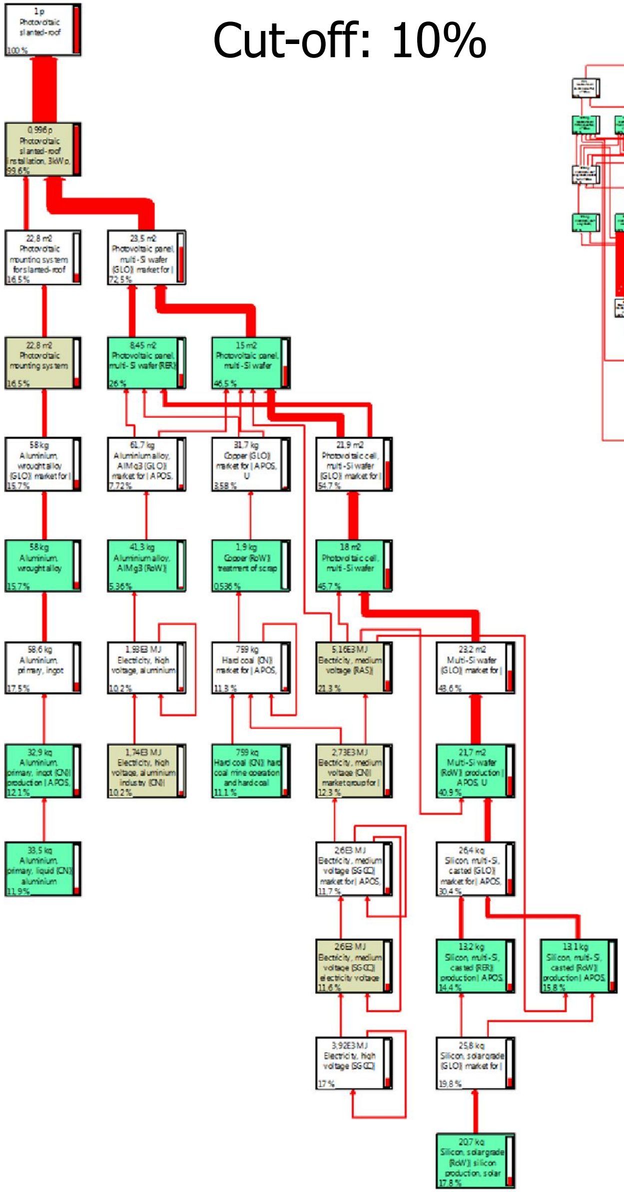
Yearly cash flows

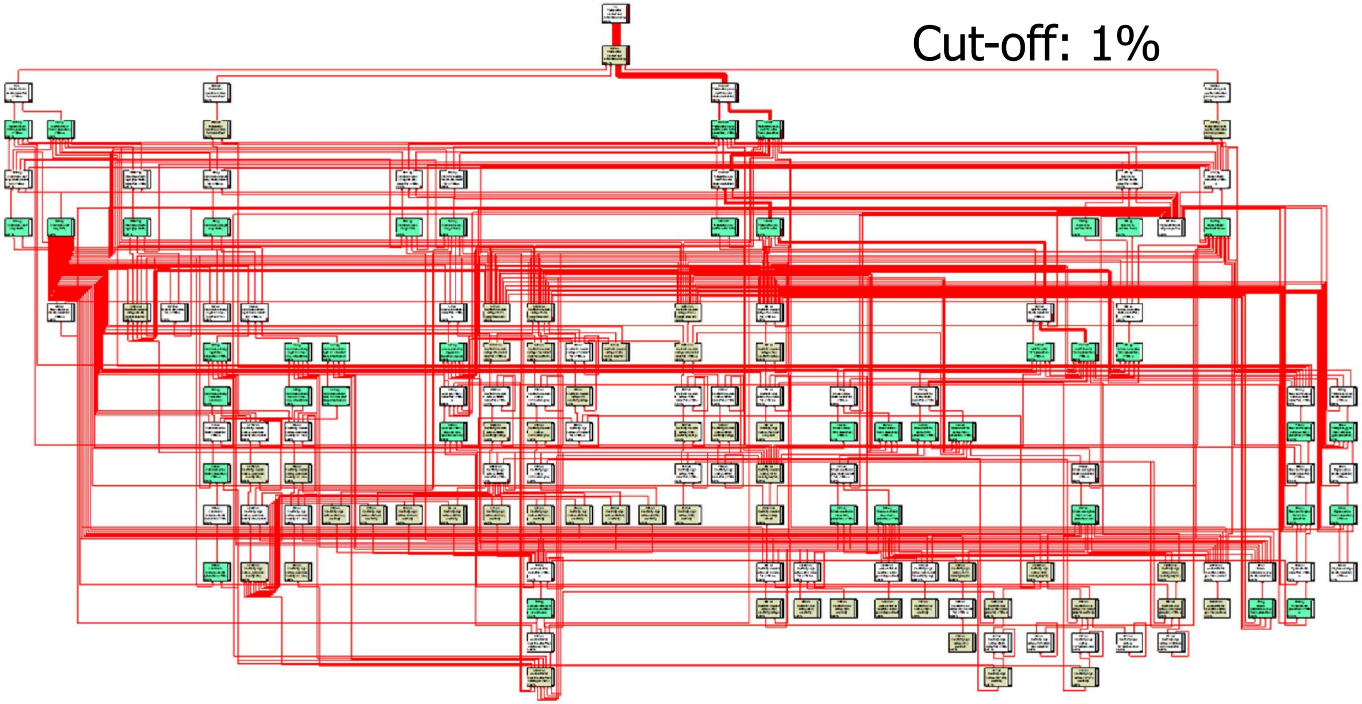
Year \#	Pre-tax €	Cumulative €
0	-14,437,228	-14,437,228
1	3,372,007	-11,065,221
2	3,439,447	-7,625,773
3	3,508,236	-4,117,537
4	3,578,401	-539,136
5	3,649,969	3,110,833
6	3,722,968	6,833,802
7	3,797,428	10,631,230
8	3,873,376	14,504,606
9	3,950,844	18,455,450
10	4,029,861	22,485,311
11	4,110,458	26,595,769
12	4,192,667	30,788,436
13	4,276,521	35,064,957
14	4,362,051	39,427,007
15	4,449,292	43,876,299
16	4,538,278	48,414,577
17	4,629,043	53,043,621
18	4,721,624	57,765,245
19	4,816,057	62,581,302
20	4,912,378	67,493,679

Yearly cash flows

- ⇨ The economic viability of both plants is virtually guaranteed, as they require a significant initial investment (€ 14.4 - 27 million € respectively) but provide very fast repayment time (~ 4.4 years) and have similar IRR rates (~ 25%). The reason for this excellent performance lies in the fact that the capacity factor of both units is 93% (or, in other words, the break time is 7%).
- ⇨ An important difference between the two plants is their life span (20 and 30 years), that affects their overall behavior, as the medium capacity geothermal plant will produce renewable electricity for 10 additional years.

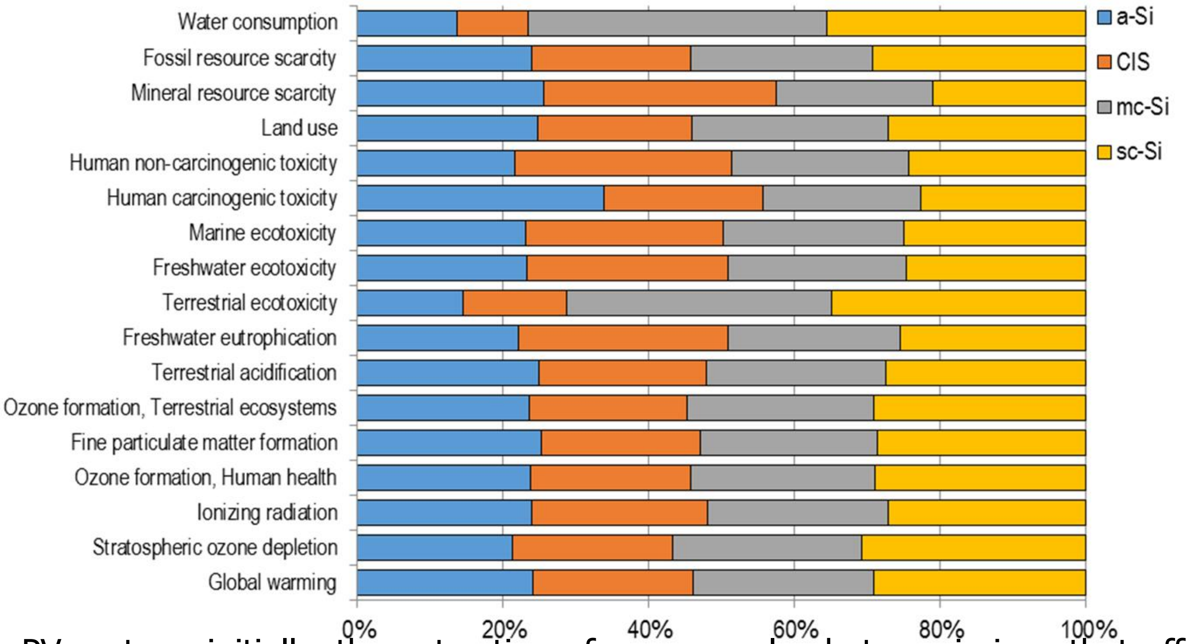
Process network
mc-Si photovoltaic system


Cut-off: 10%


Cut-off: 1%

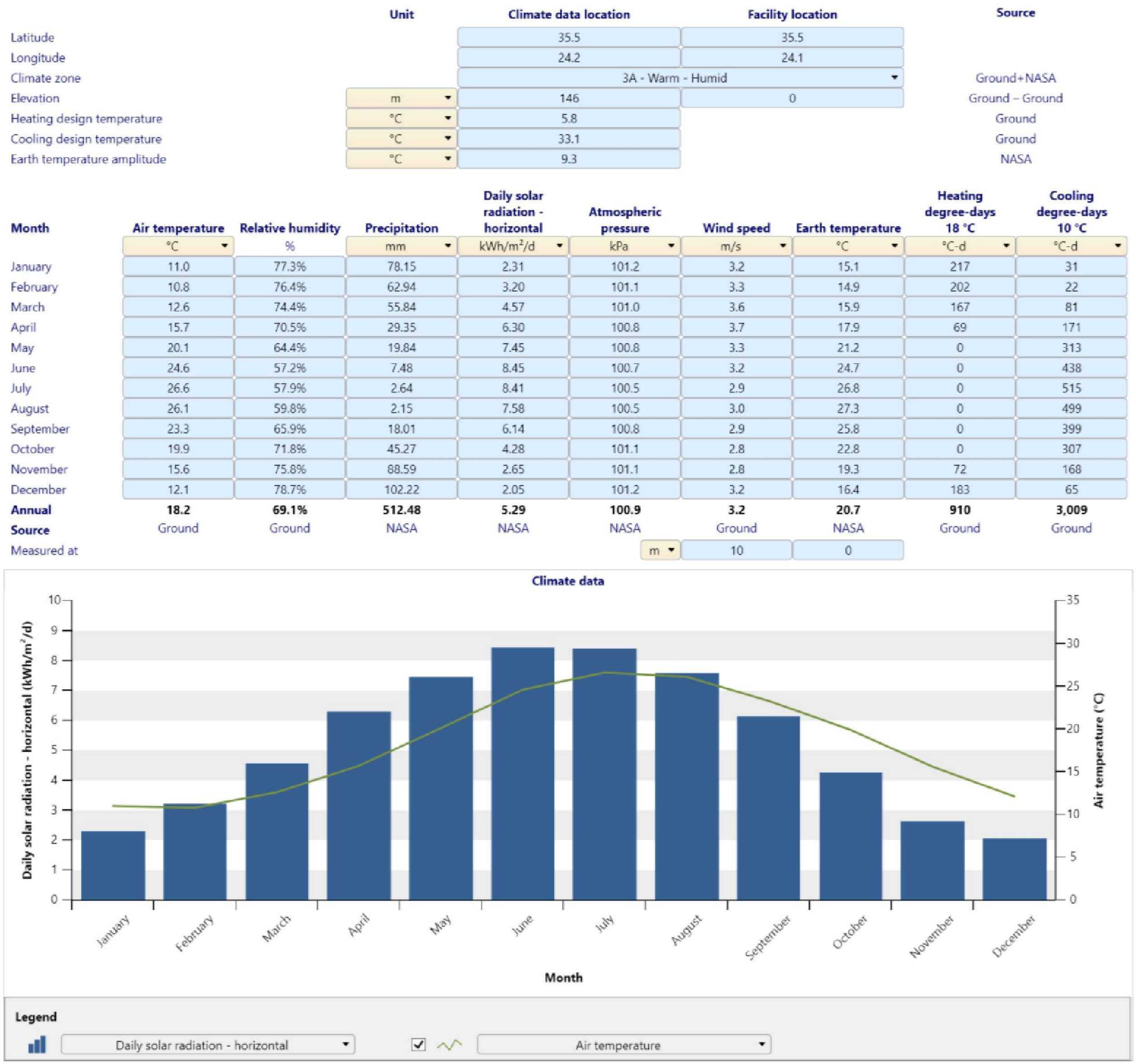
- ⇨ 72.5% of all total inflows and outflows are due to the production of the photovoltaic panel.
- ⇨ The installation phase and the inverter require 16.5% and 8.3% respectively of the energy and materials inflow.
- ⇨ There are also impacts associated with the electricity, transportation and system disposal, which are taken into consideration.

LCA results
Relative contributions to the impact categories



- During the lifecycle of a PV system, initially, the extraction of resources leads to emissions that affect human health, including carcinogens and respiratory inorganics, while at a second level the use of fossil fuel during the production and manufacturing processes releases large amounts of greenhouse gases in the atmosphere causing climate change.
- The cumulative CO_2eq emissions per kWh over the whole life cycle of the PV systems vary between approximately 3.9×10^{-2} and 5.2×10^{-2}kg CO_2eq/kWh.
- The results suggest that there are impacts on all indicators, particularly those that affect human health from substances released into the air and water.
- The crystalline technologies (mc-Si and sc-Si) have increased values in almost all impact categories. Thin-film CIS, exhibits the lower impacts in most categories and seems to be an optimum selection from an environmental perspective compared to its other counterparts.
- Thin-film technologies require less materials’ inflows for their construction and installation phases compared to crystalline systems and this coincides with reduced airborne emissions and energy. On the other hand, thin film PV systems have lower efficiencies and thus a 3kWp installation will require larger number of panels and more materials for the mounting systems.

Techno-economic analysis



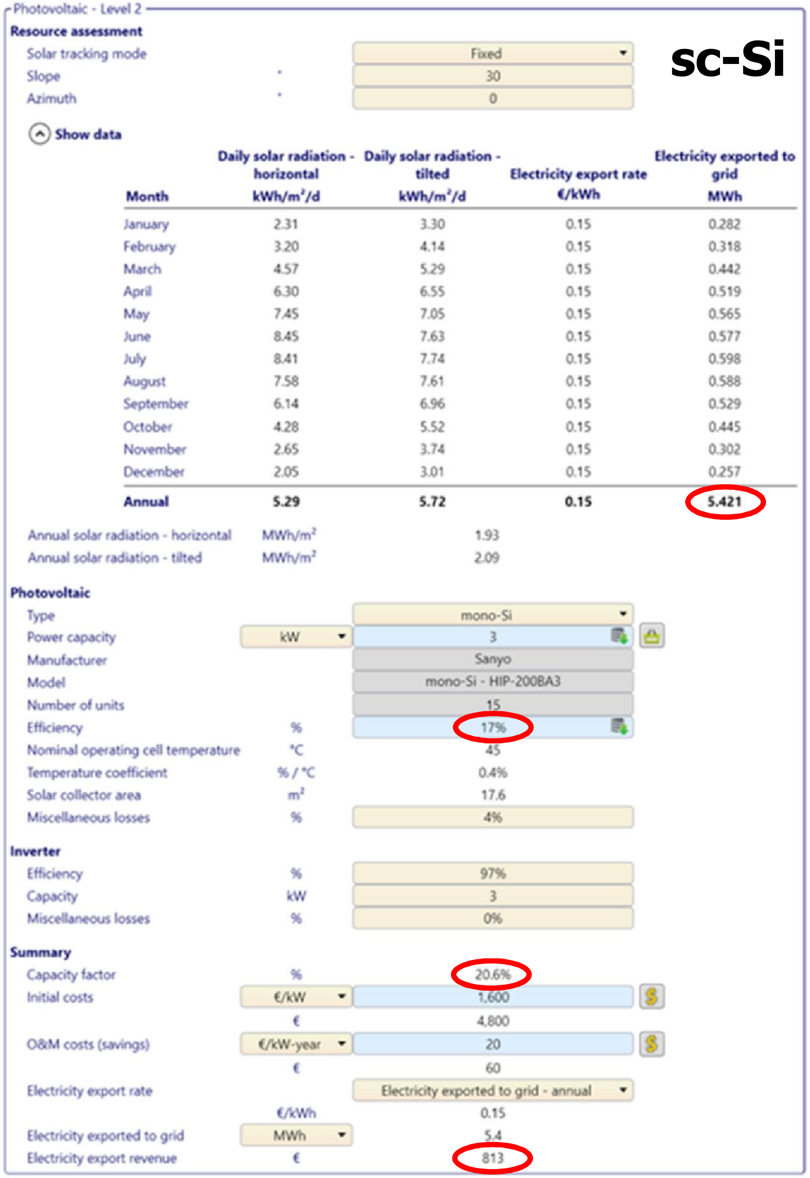
	Unit	Climate data location	Facility location	Source
Latitude		35.5	35.5	
Longitude		24.2	24.1	
Climate zone		3A - Warm - Humid		Ground+NASA
Elevation	m	146	0	Ground – Ground
Heating design temperature	°C	5.8		Ground
Cooling design temperature	°C	33.1		Ground
Earth temperature amplitude	°C	9.3		NASA

Month	Air temperature	Relative humidity	Precipitation	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days 18 °C	Cooling degree-days 10 °C
	°C	%	mm	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
January	11.0	77.3%	78.15	2.31	101.2	3.2	15.1	217	31
February	10.8	76.4%	62.94	3.20	101.1	3.3	14.9	202	22
March	12.6	74.4%	55.84	4.57	101.0	3.6	15.9	167	81
April	15.7	70.5%	29.35	6.30	100.8	3.7	17.9	69	171
May	20.1	64.4%	19.84	7.45	100.8	3.3	21.2	0	313
June	24.6	57.2%	7.48	8.45	100.7	3.2	24.7	0	438
July	26.6	57.9%	2.64	8.41	100.5	2.9	26.8	0	515
August	26.1	59.8%	2.15	7.58	100.5	3.0	27.3	0	499
September	23.3	65.9%	18.01	6.14	100.8	2.9	25.8	0	399
October	19.9	71.8%	45.27	4.28	101.1	2.8	22.8	0	307
November	15.6	75.8%	88.59	2.65	101.1	2.8	19.3	72	168
December	12.1	78.7%	102.22	2.05	101.2	3.2	16.4	183	65
Annual	**18.2**	**69.1%**	**512.48**	**5.29**	**100.9**	**3.2**	**20.7**	**910**	**3,009**
Source	Ground	Ground	NASA	NASA	NASA	Ground	NASA	Ground	Ground
Measured at					m	10	0		

Climate data

The location of the systems was chosen to be the area of Akrotiri in Chania, as it has excellent potential for incident solar radiation.

Technical specifications (PV systems)



sc-Si

Photovoltaic - Level 2

Resource assessment

Solar tracking mode		Fixed
Slope	°	30
Azimuth	°	0

Show data

Month	Daily solar radiation - horizontal kWh/m²/d	Daily solar radiation - tilted kWh/m²/d	Electricity export rate €/kWh	Electricity exported to grid MWh
January	2.31	3.30	0.15	0.282
February	3.20	4.14	0.15	0.318
March	4.57	5.29	0.15	0.442
April	6.30	6.55	0.15	0.519
May	7.45	7.05	0.15	0.565
June	8.45	7.63	0.15	0.577
July	8.41	7.74	0.15	0.598
August	7.58	7.61	0.15	0.588
September	6.14	6.96	0.15	0.529
October	4.28	5.52	0.15	0.445
November	2.65	3.74	0.15	0.302
December	2.05	3.01	0.15	0.257
Annual	**5.29**	**5.72**	**0.15**	**5.421**

Annual solar radiation - horizontal	MWh/m²	1.93
Annual solar radiation - tilted	MWh/m²	2.09

Photovoltaic

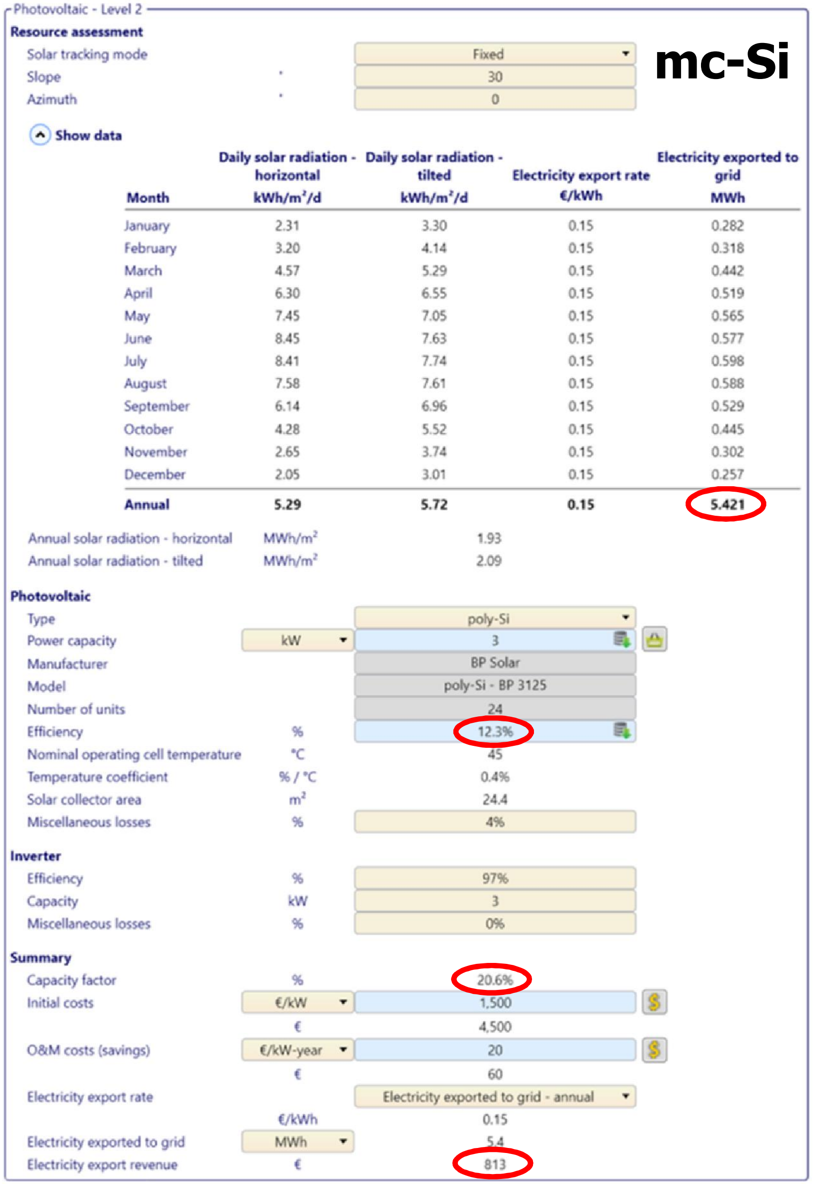
Type		mono-Si
Power capacity	kW	3
Manufacturer		Sanyo
Model		mono-Si - HIP-200BA3
Number of units		15
Efficiency	%	17%
Nominal operating cell temperature	°C	45
Temperature coefficient	% / °C	0.4%
Solar collector area	m²	17.6
Miscellaneous losses	%	4%

Inverter

Efficiency	%	97%
Capacity	kW	3
Miscellaneous losses	%	0%

Summary

Capacity factor	%	20.6%
Initial costs	€/kW	1,600
	€	4,800
O&M costs (savings)	€/kW-year	20
	€	60
Electricity export rate		Electricity exported to grid - annual
	€/kWh	0.15
Electricity exported to grid	MWh	5.4
Electricity export revenue	€	813



mc-Si

Photovoltaic - Level 2

Resource assessment

Solar tracking mode		Fixed
Slope	°	30
Azimuth	°	0

Show data

Month	Daily solar radiation - horizontal kWh/m²/d	Daily solar radiation - tilted kWh/m²/d	Electricity export rate €/kWh	Electricity exported to grid MWh
January	2.31	3.30	0.15	0.282
February	3.20	4.14	0.15	0.318
March	4.57	5.29	0.15	0.442
April	6.30	6.55	0.15	0.519
May	7.45	7.05	0.15	0.565
June	8.45	7.63	0.15	0.577
July	8.41	7.74	0.15	0.598
August	7.58	7.61	0.15	0.588
September	6.14	6.96	0.15	0.529
October	4.28	5.52	0.15	0.445
November	2.65	3.74	0.15	0.302
December	2.05	3.01	0.15	0.257
Annual	**5.29**	**5.72**	**0.15**	**5.421**

Annual solar radiation - horizontal	MWh/m²	1.93
Annual solar radiation - tilted	MWh/m²	2.09

Photovoltaic

Type		poly-Si
Power capacity	kW	3
Manufacturer		BP Solar
Model		poly-Si - BP 3125
Number of units		24
Efficiency	%	12.3%
Nominal operating cell temperature	°C	45
Temperature coefficient	% / °C	0.4%
Solar collector area	m²	24.4
Miscellaneous losses	%	4%

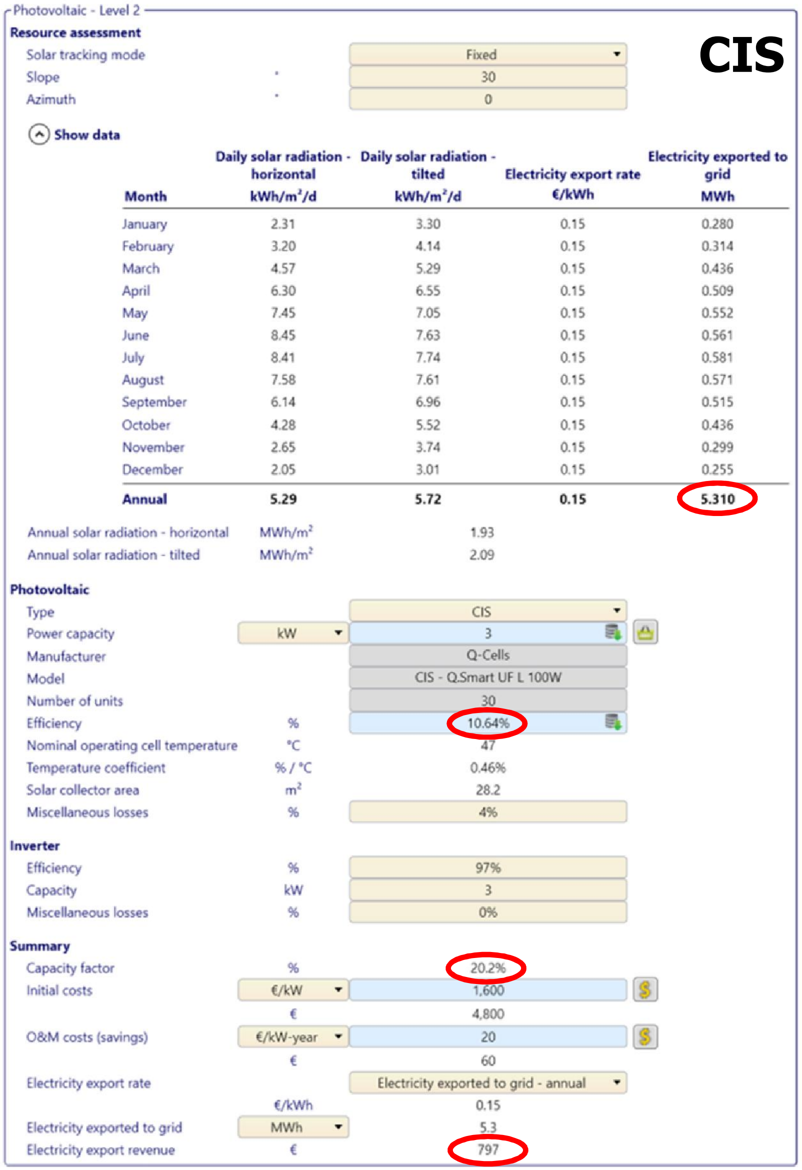
Inverter

Efficiency	%	97%
Capacity	kW	3
Miscellaneous losses	%	0%

Summary

Capacity factor	%	20.6%
Initial costs	€/kW	1,500
	€	4,500
O&M costs (savings)	€/kW-year	20
	€	60
Electricity export rate		Electricity exported to grid - annual
	€/kWh	0.15
Electricity exported to grid	MWh	5.4
Electricity export revenue	€	813

Technical specifications (PV systems)



CIS

Photovoltaic - Level 2

Resource assessment

Solar tracking mode		Fixed
Slope	°	30
Azimuth	°	0

Show data

Month	Daily solar radiation - horizontal kWh/m²/d	Daily solar radiation - tilted kWh/m²/d	Electricity export rate €/kWh	Electricity exported to grid MWh
January	2.31	3.30	0.15	0.280
February	3.20	4.14	0.15	0.314
March	4.57	5.29	0.15	0.436
April	6.30	6.55	0.15	0.509
May	7.45	7.05	0.15	0.552
June	8.45	7.63	0.15	0.561
July	8.41	7.74	0.15	0.581
August	7.58	7.61	0.15	0.571
September	6.14	6.96	0.15	0.515
October	4.28	5.52	0.15	0.436
November	2.65	3.74	0.15	0.299
December	2.05	3.01	0.15	0.255
Annual	**5.29**	**5.72**	**0.15**	**5.310**

Annual solar radiation - horizontal	MWh/m²	1.93
Annual solar radiation - tilted	MWh/m²	2.09

Photovoltaic

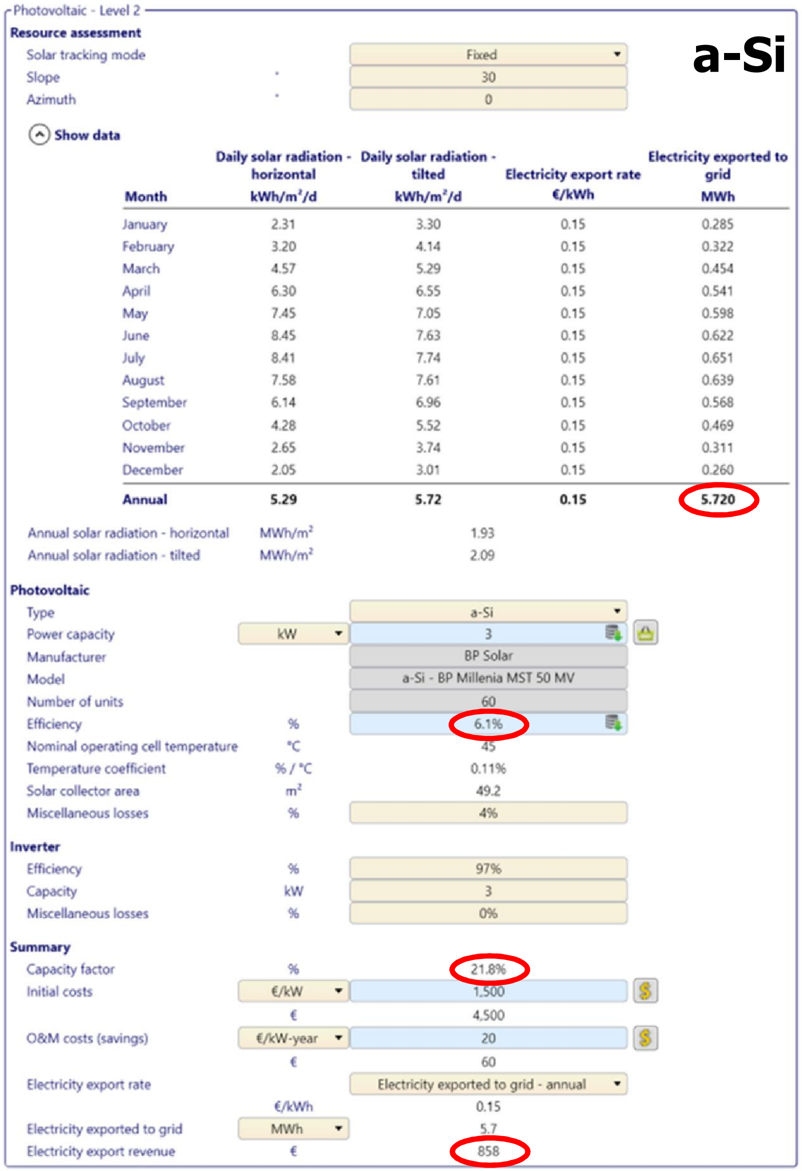
Type		CIS
Power capacity	kW	3
Manufacturer		Q-Cells
Model		CIS - Q.Smart UF L 100W
Number of units		30
Efficiency	%	10.64%
Nominal operating cell temperature	°C	47
Temperature coefficient	% / °C	0.46%
Solar collector area	m²	28.2
Miscellaneous losses	%	4%

Inverter

Efficiency	%	97%
Capacity	kW	3
Miscellaneous losses	%	0%

Summary

Capacity factor	%	20.2%
Initial costs	€/kW	1,600
	€	4,800
O&M costs (savings)	€/kW-year	20
	€	60
Electricity export rate		Electricity exported to grid - annual
	€/kWh	0.15
Electricity exported to grid	MWh	5.3
Electricity export revenue	€	797



a-Si

Photovoltaic - Level 2

Resource assessment

Solar tracking mode		Fixed
Slope	°	30
Azimuth	°	0

Show data

Month	Daily solar radiation - horizontal kWh/m²/d	Daily solar radiation - tilted kWh/m²/d	Electricity export rate €/kWh	Electricity exported to grid MWh
January	2.31	3.30	0.15	0.285
February	3.20	4.14	0.15	0.322
March	4.57	5.29	0.15	0.454
April	6.30	6.55	0.15	0.541
May	7.45	7.05	0.15	0.598
June	8.45	7.63	0.15	0.622
July	8.41	7.74	0.15	0.651
August	7.58	7.61	0.15	0.639
September	6.14	6.96	0.15	0.568
October	4.28	5.52	0.15	0.469
November	2.65	3.74	0.15	0.311
December	2.05	3.01	0.15	0.260
Annual	**5.29**	**5.72**	**0.15**	**5.720**

Annual solar radiation - horizontal	MWh/m²	1.93
Annual solar radiation - tilted	MWh/m²	2.09

Photovoltaic

Type		a-Si
Power capacity	kW	3
Manufacturer		BP Solar
Model		a-Si - BP Millenia MST 50 MV
Number of units		60
Efficiency	%	6.1%
Nominal operating cell temperature	°C	45
Temperature coefficient	% / °C	0.11%
Solar collector area	m²	49.2
Miscellaneous losses	%	4%

Inverter

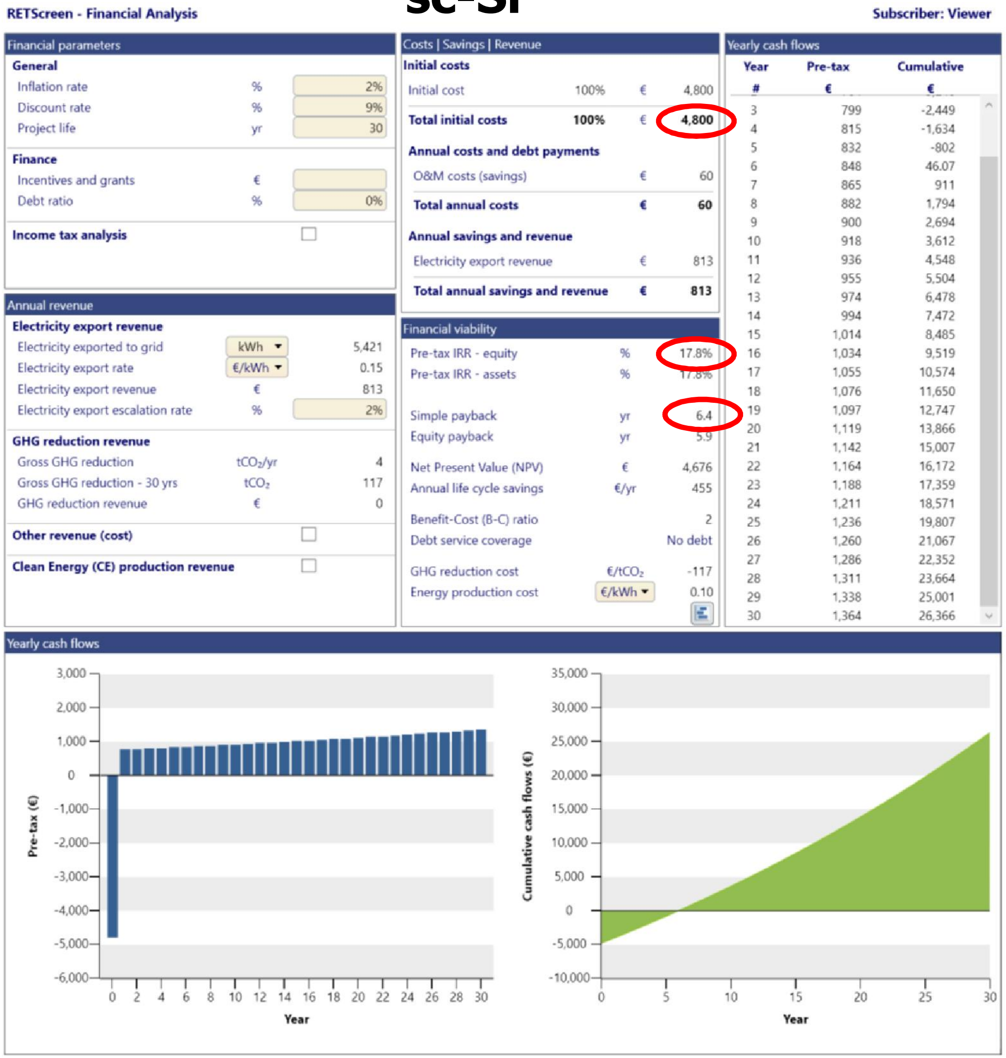
Efficiency	%	97%
Capacity	kW	3
Miscellaneous losses	%	0%

Summary

Capacity factor	%	21.8%
Initial costs	€/kW	1,500
	€	4,500
O&M costs (savings)	€/kW-year	20
	€	60
Electricity export rate		Electricity exported to grid - annual
	€/kWh	0.15
Electricity exported to grid	MWh	5.7
Electricity export revenue	€	858

Financial analysis (PV systems)

sc-Si



RETScreen - Financial Analysis

Subscriber: Viewer

Financial parameters

General		
Inflation rate	%	2%
Discount rate	%	9%
Project life	yr	30
Finance		
Incentives and grants	€	
Debt ratio	%	0%
Income tax analysis		☐

Annual revenue

Electricity export revenue		
Electricity exported to grid	kWh	5,421
Electricity export rate	€/kWh	0.15
Electricity export revenue	€	813
Electricity export escalation rate	%	2%
GHG reduction revenue		
Gross GHG reduction	tCO_2/yr	4
Gross GHG reduction - 30 yrs	tCO_2	117
GHG reduction revenue	€	0
Other revenue (cost)		☐
Clean Energy (CE) production revenue		☐

Costs | Savings | Revenue

Initial costs			
Initial cost	100%	€	4,800
Total initial costs	**100%**	€	**4,800**
Annual costs and debt payments			
O&M costs (savings)		€	60
Total annual costs		**€**	**60**
Annual savings and revenue			
Electricity export revenue		€	813
Total annual savings and revenue		**€**	**813**

Financial viability

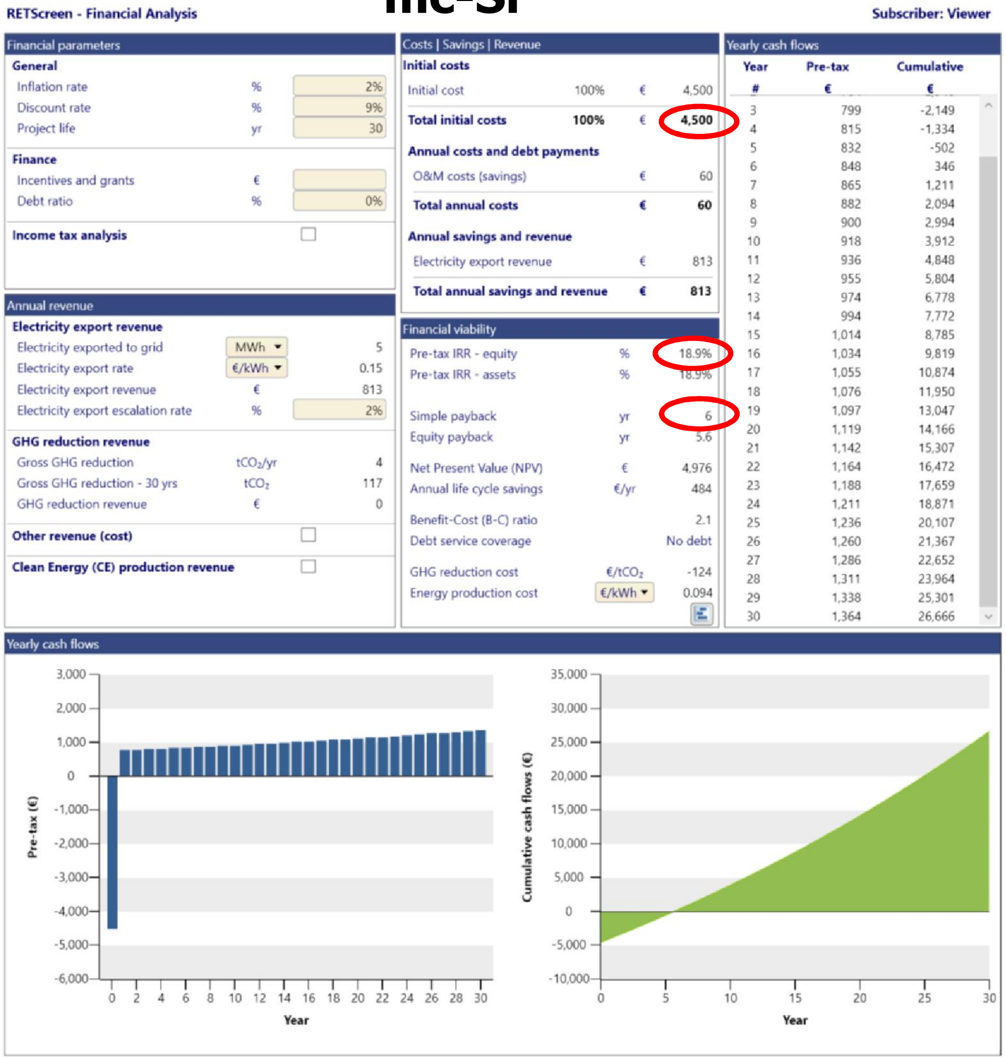
Pre-tax IRR - equity	%	17.8%
Pre-tax IRR - assets	%	17.8%
Simple payback	yr	6.4
Equity payback	yr	5.9
Net Present Value (NPV)	€	4,676
Annual life cycle savings	€/yr	455
Benefit-Cost (B-C) ratio		2
Debt service coverage		No debt
GHG reduction cost	€/tCO_2	-117
Energy production cost	€/kWh	0.10

Yearly cash flows

Year #	Pre-tax €	Cumulative €
3	799	-2,449
4	815	-1,634
5	832	-802
6	848	46.07
7	865	911
8	882	1,794
9	900	2,694
10	918	3,612
11	936	4,548
12	955	5,504
13	974	6,478
14	994	7,472
15	1,014	8,485
16	1,034	9,519
17	1,055	10,574
18	1,076	11,650
19	1,097	12,747
20	1,119	13,866
21	1,142	15,007
22	1,164	16,172
23	1,188	17,359
24	1,211	18,571
25	1,236	19,807
26	1,260	21,067
27	1,286	22,352
28	1,311	23,664
29	1,338	25,001
30	1,364	26,366

Yearly cash flows

mc-Si



RETScreen - Financial Analysis

Subscriber: Viewer

Financial parameters

General		
Inflation rate	%	2%
Discount rate	%	9%
Project life	yr	30
Finance		
Incentives and grants	€	
Debt ratio	%	0%
Income tax analysis		☐

Annual revenue

Electricity export revenue		
Electricity exported to grid	MWh	5
Electricity export rate	€/kWh	0.15
Electricity export revenue	€	813
Electricity export escalation rate	%	2%
GHG reduction revenue		
Gross GHG reduction	tCO_2/yr	4
Gross GHG reduction - 30 yrs	tCO_2	117
GHG reduction revenue	€	0
Other revenue (cost)		☐
Clean Energy (CE) production revenue		☐

Costs | Savings | Revenue

Initial costs			
Initial cost	100%	€	4,500
Total initial costs	**100%**	€	**4,500**
Annual costs and debt payments			
O&M costs (savings)		€	60
Total annual costs		**€**	**60**
Annual savings and revenue			
Electricity export revenue		€	813
Total annual savings and revenue		**€**	**813**

Financial viability

Pre-tax IRR - equity	%	18.9%
Pre-tax IRR - assets	%	18.9%
Simple payback	yr	6
Equity payback	yr	5.6
Net Present Value (NPV)	€	4,976
Annual life cycle savings	€/yr	484
Benefit-Cost (B-C) ratio		2.1
Debt service coverage		No debt
GHG reduction cost	€/tCO_2	-124
Energy production cost	€/kWh	0.094

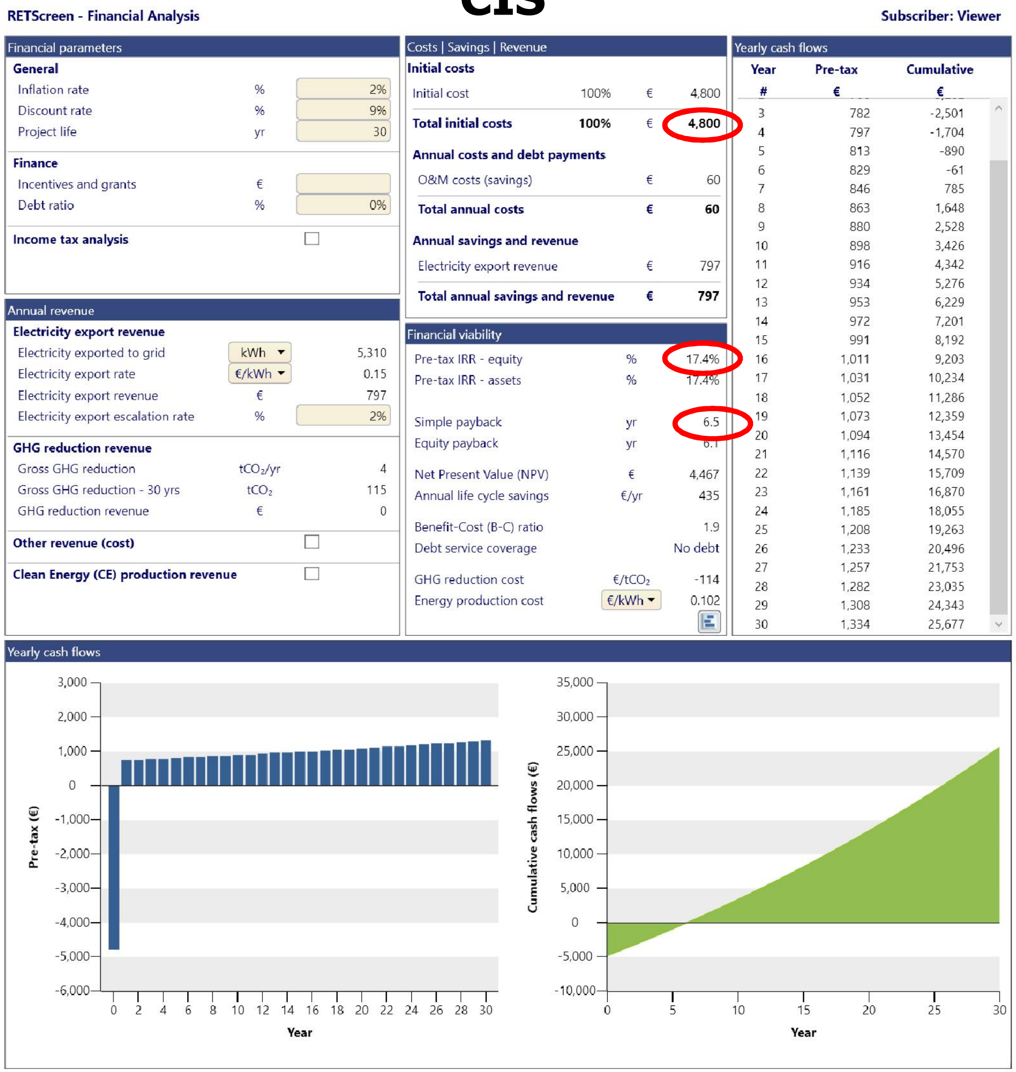
Yearly cash flows

Year #	Pre-tax €	Cumulative €
3	799	-2,149
4	815	-1,334
5	832	-502
6	848	346
7	865	1,211
8	882	2,094
9	900	2,994
10	918	3,912
11	936	4,848
12	955	5,804
13	974	6,778
14	994	7,772
15	1,014	8,785
16	1,034	9,819
17	1,055	10,874
18	1,076	11,950
19	1,097	13,047
20	1,119	14,166
21	1,142	15,307
22	1,164	16,472
23	1,188	17,659
24	1,211	18,871
25	1,236	20,107
26	1,260	21,367
27	1,286	22,652
28	1,311	23,964
29	1,338	25,301
30	1,364	26,666

Yearly cash flows

Financial analysis (PV systems)

CIS



RETScreen - Financial Analysis

Subscriber: Viewer

Financial parameters

General

Inflation rate	%	2%
Discount rate	%	9%
Project life	yr	30

Finance

Incentives and grants	€	
Debt ratio	%	0%

Income tax analysis ☐

Annual revenue

Electricity export revenue

Electricity exported to grid	kWh ▾	5,310
Electricity export rate	€/kWh ▾	0.15
Electricity export revenue	€	797
Electricity export escalation rate	%	2%

GHG reduction revenue

Gross GHG reduction	tCO_2/yr	4
Gross GHG reduction - 30 yrs	tCO_2	115
GHG reduction revenue	€	0

Other revenue (cost) ☐

Clean Energy (CE) production revenue ☐

Costs | Savings | Revenue

Initial costs

Initial cost	100%	€	4,800
Total initial costs	**100%**	€	**4,800**

Annual costs and debt payments

O&M costs (savings)	€	60
Total annual costs	**€**	**60**

Annual savings and revenue

Electricity export revenue	€	797
Total annual savings and revenue	**€**	**797**

Financial viability

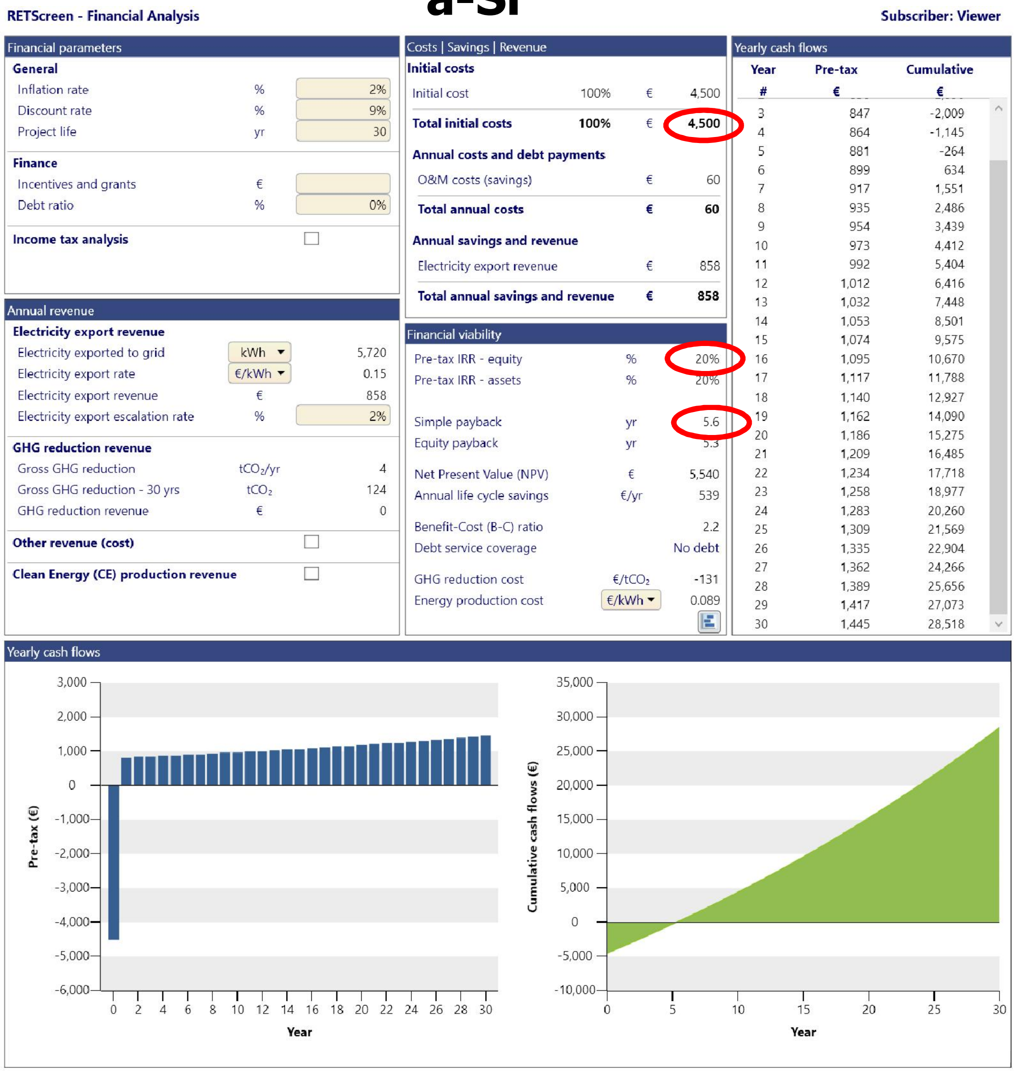
Pre-tax IRR - equity	%	17.4%
Pre-tax IRR - assets	%	17.4%
Simple payback	yr	6.5
Equity payback	yr	6.1
Net Present Value (NPV)	€	4,467
Annual life cycle savings	€/yr	435
Benefit-Cost (B-C) ratio		1.9
Debt service coverage		No debt
GHG reduction cost	€/tCO_2	-114
Energy production cost	€/kWh ▾	0.102

Yearly cash flows

Year	Pre-tax	Cumulative
#	€	€
3	782	-2,501
4	797	-1,704
5	813	-890
6	829	-61
7	846	785
8	863	1,648
9	880	2,528
10	898	3,426
11	916	4,342
12	934	5,276
13	953	6,229
14	972	7,201
15	991	8,192
16	1,011	9,203
17	1,031	10,234
18	1,052	11,286
19	1,073	12,359
20	1,094	13,454
21	1,116	14,570
22	1,139	15,709
23	1,161	16,870
24	1,185	18,055
25	1,208	19,263
26	1,233	20,496
27	1,257	21,753
28	1,282	23,035
29	1,308	24,343
30	1,334	25,677

Yearly cash flows

a-Si



RETScreen - Financial Analysis

Subscriber: Viewer

Financial parameters

General

Inflation rate	%	2%
Discount rate	%	9%
Project life	yr	30

Finance

Incentives and grants	€	
Debt ratio	%	0%

Income tax analysis ☐

Annual revenue

Electricity export revenue

Electricity exported to grid	kWh ▾	5,720
Electricity export rate	€/kWh ▾	0.15
Electricity export revenue	€	858
Electricity export escalation rate	%	2%

GHG reduction revenue

Gross GHG reduction	tCO_2/yr	4
Gross GHG reduction - 30 yrs	tCO_2	124
GHG reduction revenue	€	0

Other revenue (cost) ☐

Clean Energy (CE) production revenue ☐

Costs | Savings | Revenue

Initial costs

Initial cost	100%	€	4,500
Total initial costs	**100%**	€	**4,500**

Annual costs and debt payments

O&M costs (savings)	€	60
Total annual costs	**€**	**60**

Annual savings and revenue

Electricity export revenue	€	858
Total annual savings and revenue	**€**	**858**

Financial viability

Pre-tax IRR - equity	%	20%
Pre-tax IRR - assets	%	20%
Simple payback	yr	5.6
Equity payback	yr	5.3
Net Present Value (NPV)	€	5,540
Annual life cycle savings	€/yr	539
Benefit-Cost (B-C) ratio		2.2
Debt service coverage		No debt
GHG reduction cost	€/tCO_2	-131
Energy production cost	€/kWh ▾	0.089

Yearly cash flows

Year	Pre-tax	Cumulative
#	€	€
3	847	-2,009
4	864	-1,145
5	881	-264
6	899	634
7	917	1,551
8	935	2,486
9	954	3,439
10	973	4,412
11	992	5,404
12	1,012	6,416
13	1,032	7,448
14	1,053	8,501
15	1,074	9,575
16	1,095	10,670
17	1,117	11,788
18	1,140	12,927
19	1,162	14,090
20	1,186	15,275
21	1,209	16,485
22	1,234	17,718
23	1,258	18,977
24	1,283	20,260
25	1,309	21,569
26	1,335	22,904
27	1,362	24,266
28	1,389	25,656
29	1,417	27,073
30	1,445	28,518

Yearly cash flows

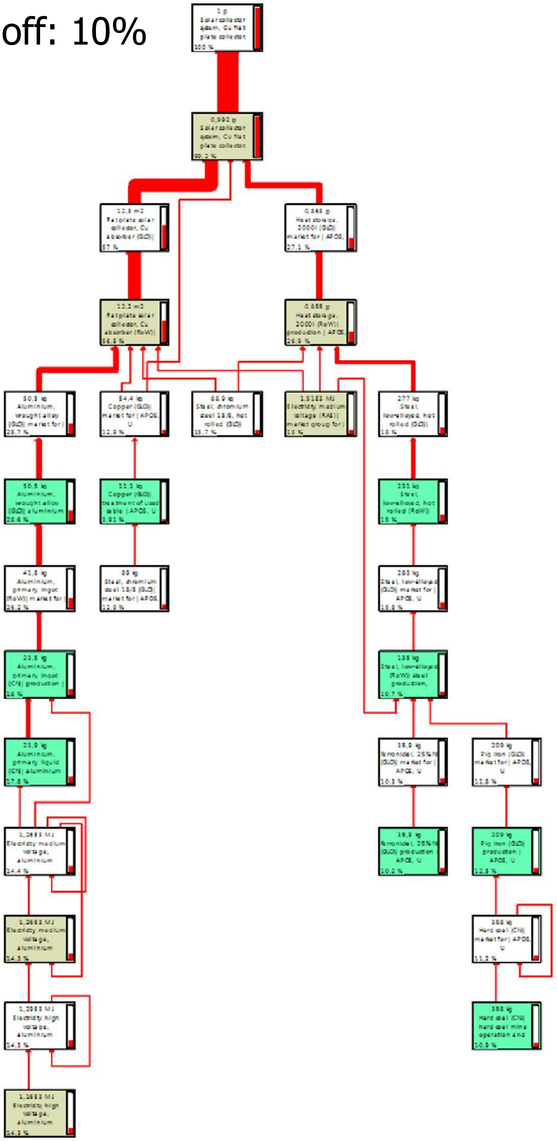
Techno-economic assessment (PV systems)

PV technology	Cell efficiency [%]	Frame area [m²]	Capacity per unit [W]	Total area [m²]	Cost [€/kW]	Capacity factor [%]	Total electricity exported to grid [MWh]	Annual revenue [€/yr]	IRR [%]	Payback time [years]
sc-Si	17	1.18	200	17.7	1600	20.6	162.6	813	17.8	6.4
mc-Si	12.3	1.02	125	24.5	1500	20.6	162.6	813	18.9	6
CIS	10.6	0.94	100	28.2	1600	20.2	159.3	797	17.4	6.5
a-Si	6.1	0.82	50	49.2	1500	21.8	171.6	858	20.0	5.6

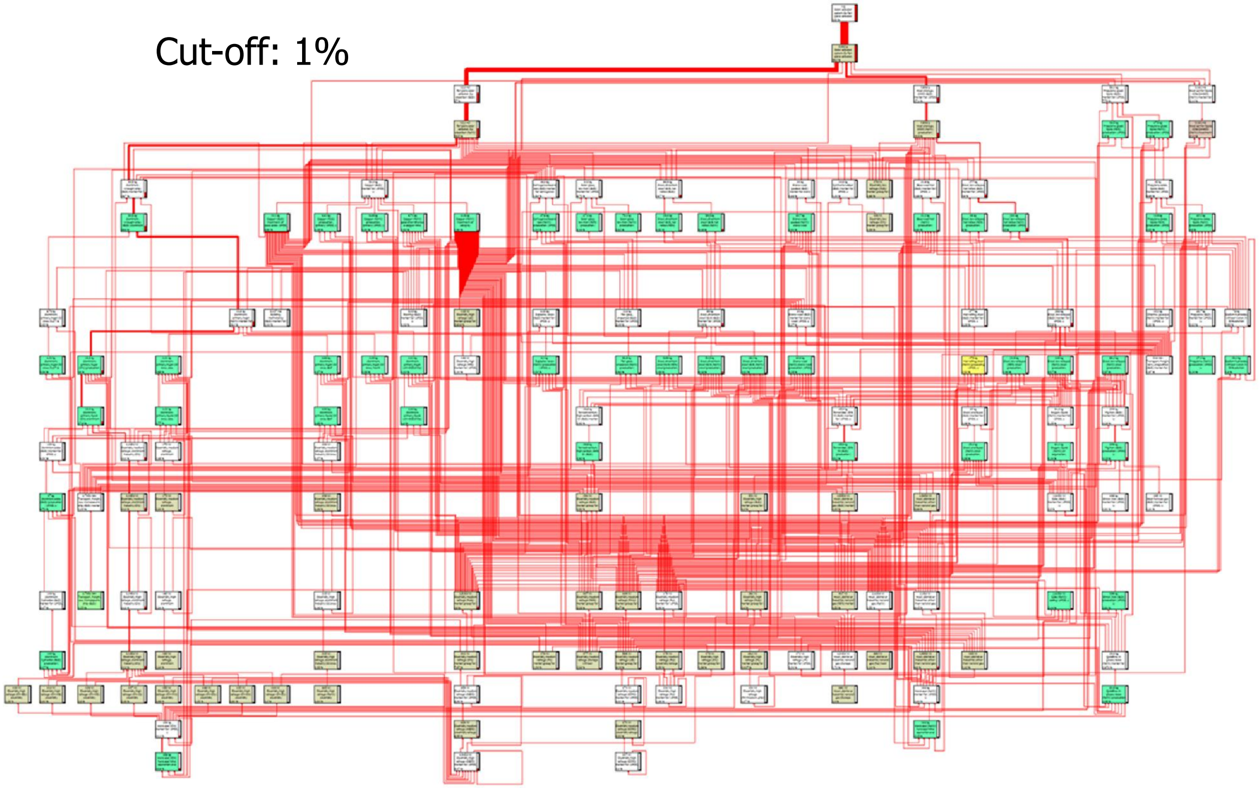
- The cell efficiencies of the PV systems vary (from 6.1% to 17%) but this parameter does not play an important role as the nominal capacity of all systems is set to 3 kW.
- The larger the efficiency of the panel the less the area needed for the installation (from 17.7m² to 49.2m²).
- The a-Si system seems to have higher annual energy yield. This is practically due to the ability of these systems to produce more electricity under low sunshine or cloudy conditions and thus their capacity factor is increased (21.8%) compared to their counterparts.
- The economic viability of all systems is obvious, as the simple payback period is 5.6 - 6.5 years and IRR values vary from 17.4% to 20%.
- The electricity produced allows for the mitigation of ~4 tons of CO_2eq annually for all PV systems.
- The anticipated energy production, emissions reduction, investment cost, financial viability and risks associated with the four technologies are approximately the same. All technologies portray relatively equal cost benefit ratios and financial parameters. This is mainly due to the fact that our selection of comparing 3kWp systems harmonizes the influence of all technical advantages amongst technologies. On the other hand, the sc-Si system is the most efficient per cell thus needing less area per installation compared to the other cases.

Process network (flat plate collector)

Cut-off: 10%



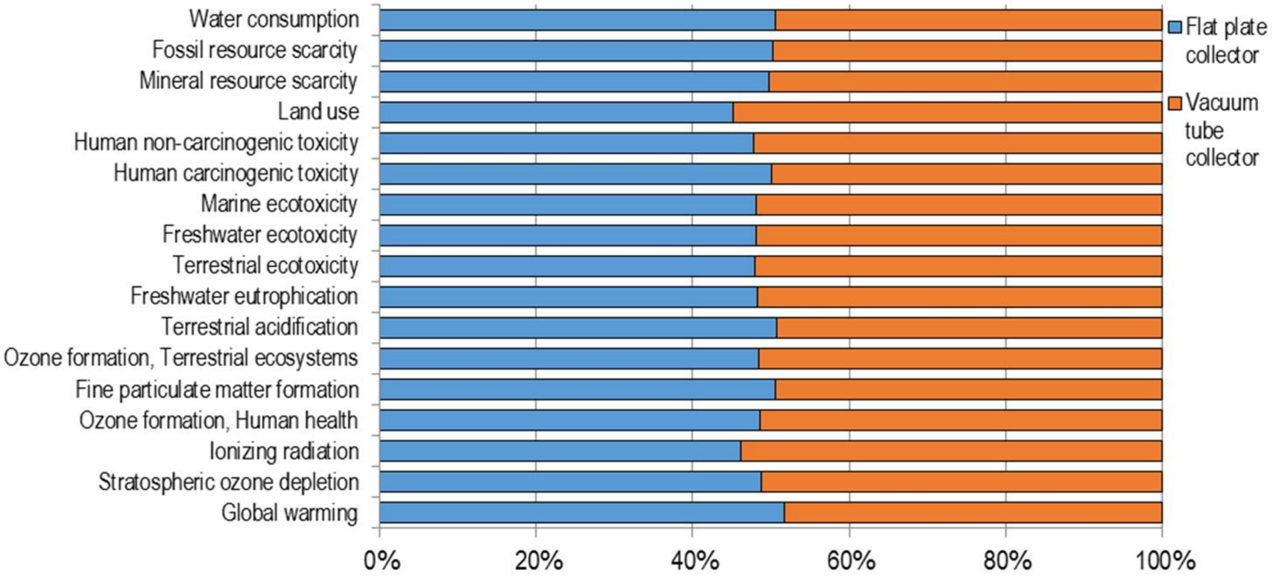
Cut-off: 1%



- 57% of all total inflows and outflows are due to the production of the collector.
- 27.1% of the energy and materials inflow is due to the production of the tank.
- There are also impacts associated with the electricity production, transportation and system disposal which are taken into consideration.

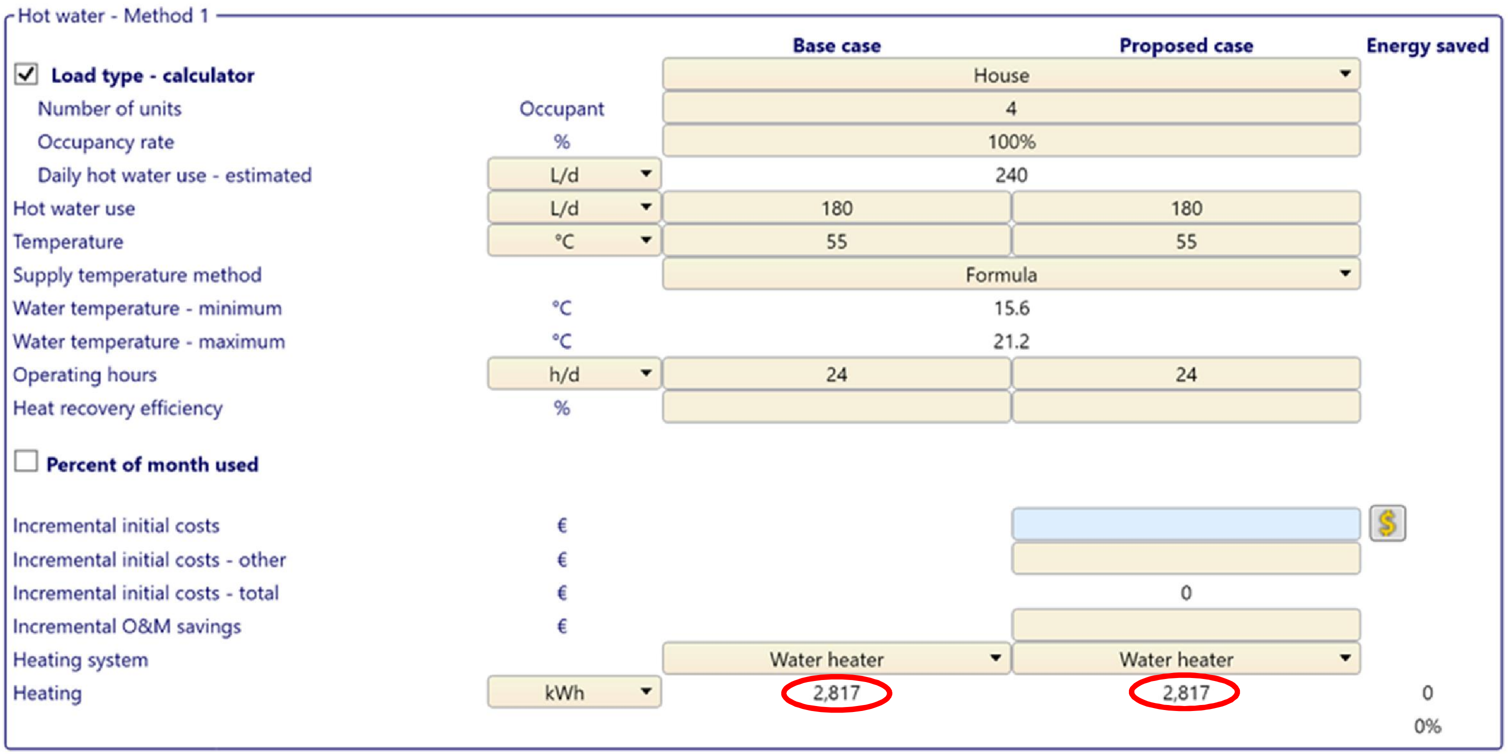
LCA results

Relative contributions to the impact categories



- The cumulative CO_2eq emissions over the whole life cycle of the solar systems are quite close, varying between 2.22×10^{-2} and 2.38×10^{-2} kg CO_2eq/kWh·m^2 and the lowest value corresponds to the vacuum tube collector.
- Electricity (in kWh) corresponds to the energy needed for heating water, which is saved by the operation of solar panels that convert solar radiation into heat and ultimately stored hot water.
- The results of the relative contributions to the impact categories (based on the ReCiPe 2016 midpoint evaluation) are mixed with the two systems exhibiting similar environmental impacts in most categories, but the vacuum tube collector has highest values in most cases.

Annual hot water needs for the studied house



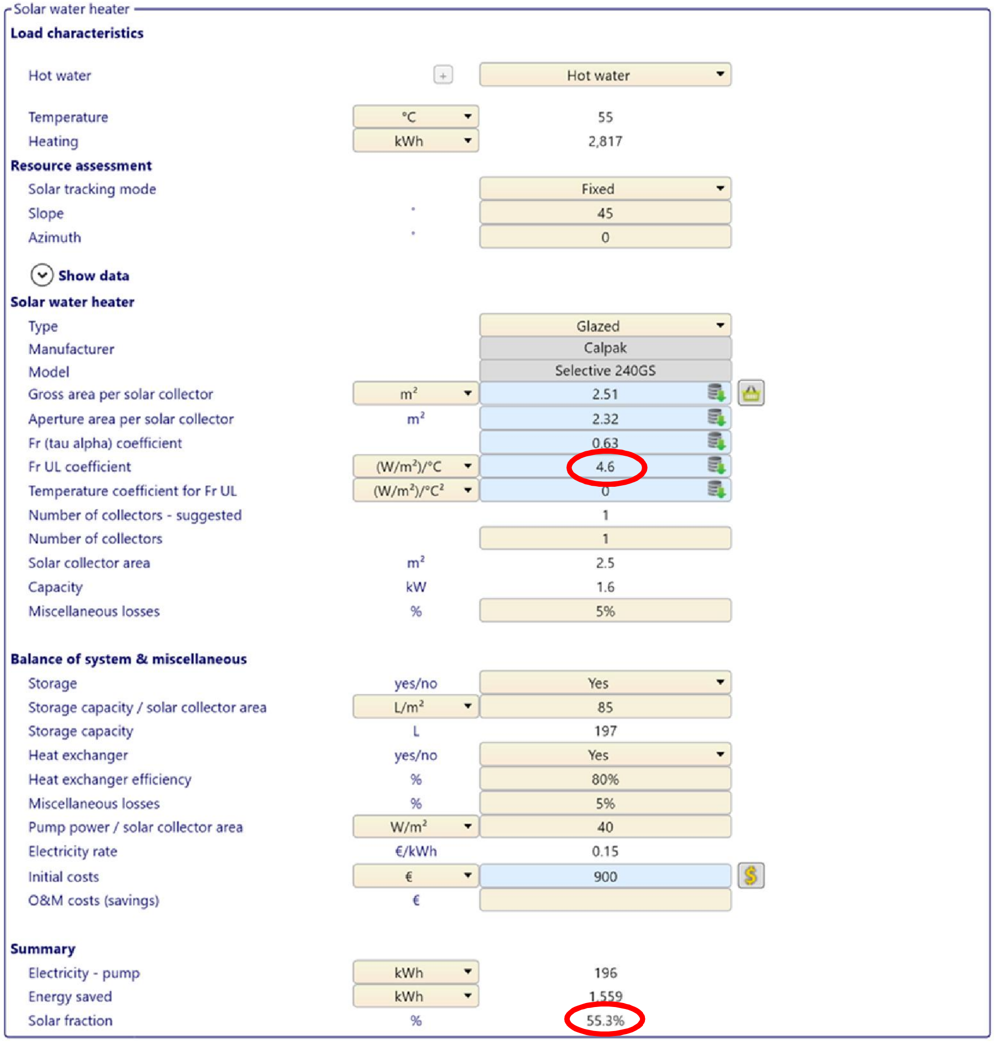
Hot water - Method 1

		Base case	Proposed case	Energy saved
☑ **Load type - calculator**		House		
Number of units	Occupant	4		
Occupancy rate	%	100%		
Daily hot water use - estimated	L/d	240		
Hot water use	L/d	180	180	
Temperature	°C	55	55	
Supply temperature method		Formula		
Water temperature - minimum	°C	15.6		
Water temperature - maximum	°C	21.2		
Operating hours	h/d	24	24	
Heat recovery efficiency	%			
☐ **Percent of month used**				
Incremental initial costs	€			
Incremental initial costs - other	€			
Incremental initial costs - total	€		0	
Incremental O&M savings	€			
Heating system		Water heater	Water heater	
Heating	kWh	2,817	2,817	0
				0%

- The energy needs for hot water supply for a typical family house with 4 occupants (taking as granted 100% occupancy rate and 24 operating hours per day) have been estimated to **2817kWh/year**. A typical auxiliary hot water heating system burning oil has been considered for backup.
- Both selected solar thermal collector systems can be considered as high quality products, while the purchase cost of the vacuum tube collector is significantly higher, i.e. **1300 €** versus **900 €**.

Technical specifications (solar collectors)

Flat plate collector



Solar water heater

Load characteristics

Hot water		Hot water
Temperature	°C	55
Heating	kWh	2,817

Resource assessment

Solar tracking mode		Fixed
Slope	°	45
Azimuth	°	0

Show data

Solar water heater

Type		Glazed
Manufacturer		Calpak
Model		Selective 240GS
Gross area per solar collector	m^2	2.51
Aperture area per solar collector	m^2	2.32
Fr (tau alpha) coefficient		0.63
Fr UL coefficient	$(W/m^2)/°C$	4.6
Temperature coefficient for Fr UL	$(W/m^2)/°C^2$	0
Number of collectors - suggested		1
Number of collectors		1
Solar collector area	m^2	2.5
Capacity	kW	1.6
Miscellaneous losses	%	5%

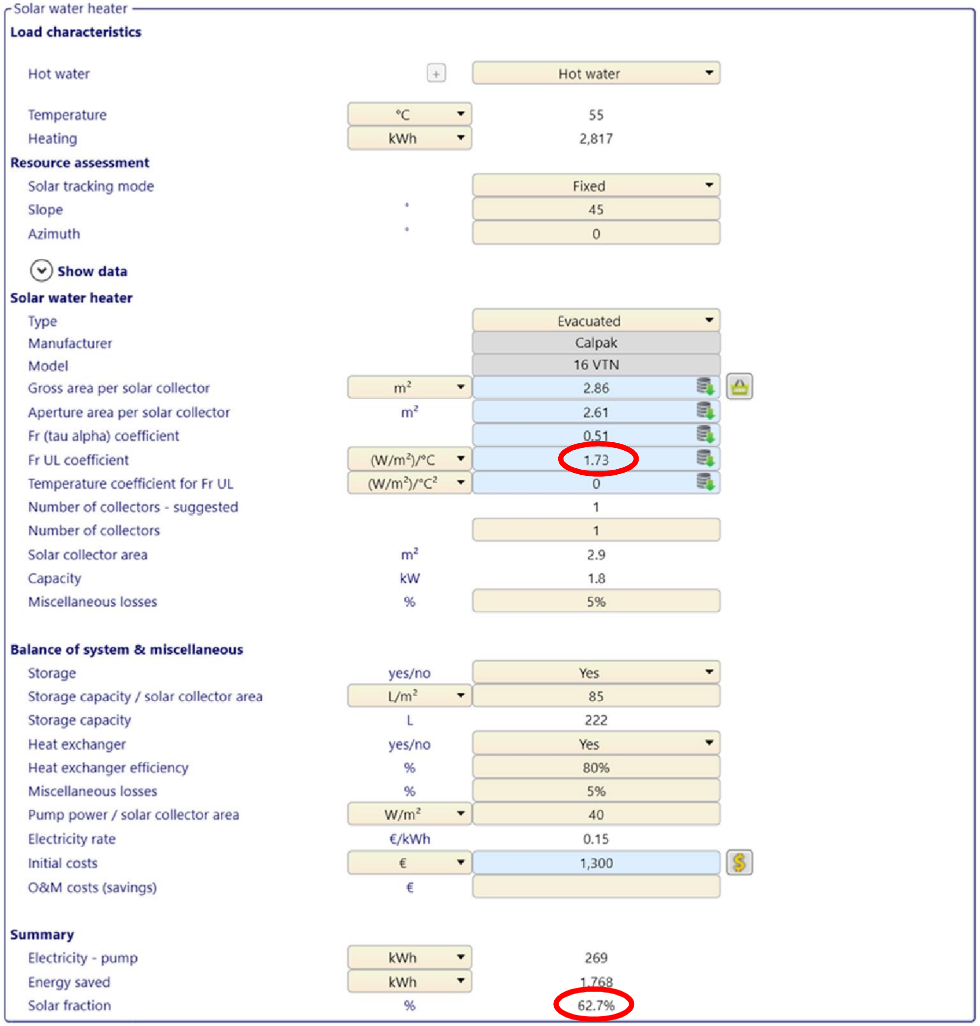
Balance of system & miscellaneous

Storage	yes/no	Yes
Storage capacity / solar collector area	L/m^2	85
Storage capacity	L	197
Heat exchanger	yes/no	Yes
Heat exchanger efficiency	%	80%
Miscellaneous losses	%	5%
Pump power / solar collector area	W/m^2	40
Electricity rate	€/kWh	0.15
Initial costs	€	900
O&M costs (savings)	€	

Summary

Electricity - pump	kWh	196
Energy saved	kWh	1,559
Solar fraction	%	55.3%

Vacuum tube collector



Solar water heater

Load characteristics

Hot water		Hot water
Temperature	°C	55
Heating	kWh	2,817

Resource assessment

Solar tracking mode		Fixed
Slope	°	45
Azimuth	°	0

Show data

Solar water heater

Type		Evacuated
Manufacturer		Calpak
Model		16 VTN
Gross area per solar collector	m^2	2.86
Aperture area per solar collector	m^2	2.61
Fr (tau alpha) coefficient		0.51
Fr UL coefficient	$(W/m^2)/°C$	1.73
Temperature coefficient for Fr UL	$(W/m^2)/°C^2$	0
Number of collectors - suggested		1
Number of collectors		1
Solar collector area	m^2	2.9
Capacity	kW	1.8
Miscellaneous losses	%	5%

Balance of system & miscellaneous

Storage	yes/no	Yes
Storage capacity / solar collector area	L/m^2	85
Storage capacity	L	222
Heat exchanger	yes/no	Yes
Heat exchanger efficiency	%	80%
Miscellaneous losses	%	5%
Pump power / solar collector area	W/m^2	40
Electricity rate	€/kWh	0.15
Initial costs	€	1,300
O&M costs (savings)	€	

Summary

Electricity - pump	kWh	269
Energy saved	kWh	1,768
Solar fraction	%	62.7%

Financial analysis results (solar collectors)

Flat plate collector

Financial parameters

General		
Fuel cost escalation rate	%	2%
Inflation rate	%	2%
Discount rate	%	9%
Project life	yr	20
Finance		
Incentives and grants	€	
Debt ratio	%	0%
Income tax analysis	☐	

Annual revenue

GHG reduction revenue		
Gross GHG reduction	tCO_2/yr	1
Gross GHG reduction - 20 yrs	tCO_2	26
GHG reduction revenue	€	0
Other revenue (cost)	☐	

Costs | Savings | Revenue

Initial costs			
Incremental initial costs	100%	€	900
Total initial costs	**100%**	€	**900**
Annual costs and debt payments			
O&M costs (savings)		€	0
Fuel cost - proposed case		€	29
Total annual costs		**€**	**29**
Annual savings and revenue			
Fuel cost - base case		€	381
Total annual savings and revenue		**€**	**381**

Financial viability

Pre-tax IRR - equity	%	41.8%
Pre-tax IRR - assets	%	41.8%
Simple payback	yr	2.6
Equity payback	yr	2.5
Net Present Value (NPV)	€	2,869
Annual life cycle savings	€/yr	314
Benefit-Cost (B-C) ratio		4.2
Debt service coverage		No debt
GHG reduction cost	$€/tCO_2$	-242

Yearly cash flows

Year	Pre-tax	Cumulative
#	€	€
0	-900	-900
1	359	-541
2	366	-175
3	374	199
4	381	580
5	389	968
6	396	1,365
7	404	1,769
8	412	2,181
9	421	2,602
10	429	3,031
11	438	3,469
12	446	3,915
13	455	4,370
14	464	4,835
15	474	5,309
16	483	5,792
17	493	6,285
18	503	6,787
19	513	7,300
20	523	7,823

Vacuum tube collector

Financial parameters

General		
Fuel cost escalation rate	%	2%
Inflation rate	%	2%
Discount rate	%	9%
Project life	yr	20
Finance		
Incentives and grants	€	
Debt ratio	%	0%
Income tax analysis	☐	

Annual revenue

GHG reduction revenue		
Gross GHG reduction	tCO_2/yr	1
Gross GHG reduction - 20 yrs	tCO_2	25
GHG reduction revenue	€	0
Other revenue (cost)	☐	

Costs | Savings | Revenue

Initial costs			
Incremental initial costs	100%	€	1,300
Total initial costs	**100%**	€	**1,300**
Annual costs and debt payments			
O&M costs (savings)		€	0
Fuel cost - proposed case		€	40
Total annual costs		**€**	**40**
Annual savings and revenue			
Fuel cost - base case		€	381
Total annual savings and revenue		**€**	**381**

Financial viability

Pre-tax IRR - equity	%	28.5%
Pre-tax IRR - assets	%	28.5%
Simple payback	yr	3.8
Equity payback	yr	3.6
Net Present Value (NPV)	€	2,351
Annual life cycle savings	€/yr	258
Benefit-Cost (B-C) ratio		2.8
Debt service coverage		No debt
GHG reduction cost	$€/tCO_2$	-208

Yearly cash flows

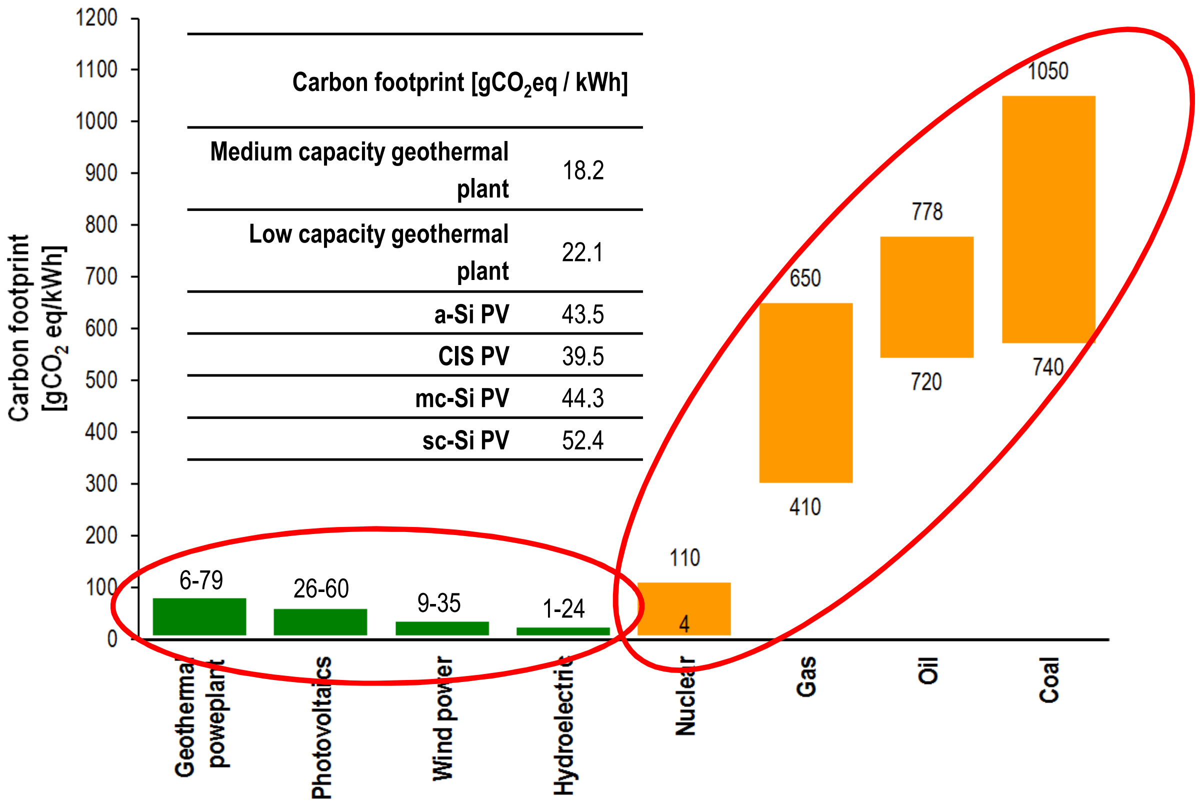
Year	Pre-tax	Cumulative
#	€	€
0	-1,300	-1,300
1	348	-952
2	355	-597
3	362	-236
4	369	133
5	376	510
6	384	894
7	392	1,286
8	400	1,685
9	407	2,093
10	416	2,508
11	424	2,932
12	432	3,365
13	441	3,806
14	450	4,255
15	459	4,714
16	468	5,182
17	477	5,660
18	487	6,147
19	497	6,644
20	507	7,150

Techno-economic assessment

Solar collector type	Aperture area [m^2]	F_rUL [(W/m^2)/°C]	Cost [€]	Total energy saved [kWh]	Total energy saved per aperture area [kWh/m^2]	Solar fraction [%]	Annual savings [€/yr]	IRR [%]	Payback time [years]
Flat plate	2.32	4.6	900	27260	11750	55.3	352	41.8	2.6
Vacuum tube	2.61	1.7	1300	29980	11487	62.7	341	28.5	3.8

- The thermal losses coefficient (FrUL) is increased for the flat plate collector compared to the vacuum tube system, i.e. **4.6** vs **1.7** (W/m2)/°C respectively. This is due to the completely different thermal losses suppression design followed in each system, which practically makes vacuum tube collector unaffected by variations in ambient temperature. Additionally, the vacuum tube system covers the annually hot water needs in a percentage of **62.7%** compared to **55.3%** of the flat collector.
- It is evident that overall this parameter does not play an important role in the energy outcome of the systems, as finally the flat plate collector provides slightly more energy per aperture area throughout the year. This is mainly due to two reasons: i. the weather conditions in Crete (high intensity solar radiation for extended time periods and with increased ambient temperatures throughout the year) are favorable for solar systems and thus the advantageous thermal insulation and the ability to reach high temperatures of the vacuum system is not necessary, ii. the pump in the vacuum system requires more electricity due to increased friction in the collector (more complex circulation system).
- The economic viability of the two systems is obvious: the simple payback period is **2.6** and **3.8** years and IRR values **41.8%** and **28.5%** for the flat plate and the vacuum tube system respectively.
- The above mentioned results prove that the selection of a flat plate system is rather mandatory for typical installations in Crete while vacuum tube systems could be selected for demanding applications.

Comparative assessment of technologies



Carbon footprint [gCO$_2$eq / kWh]	
Medium capacity geothermal plant	18.2
Low capacity geothermal plant	22.1
a-Si PV	43.5
CIS PV	39.5
mc-Si PV	44.3
sc-Si PV	52.4

- ⇨ The carbon footprint evaluates the environmental emissions per unit of energy produced (usually in gCO$_2$eq / kWh).
- ⇨ The carbon footprint for geothermal systems is lower compared to photovoltaic systems, and both technologies together with other renewable (wind, hydro) and nuclear power plants are far from conventional fossil fuel power plants (which show values ranging from 400-1050).