LIFE CYCLE ASSESSMENT AND ECO-DESIGN ALTERNATIVES OF SOLAR THERMAL TECHNOLOGIES FOR THE PROMOTION OF CIRCULAR ECONOMY

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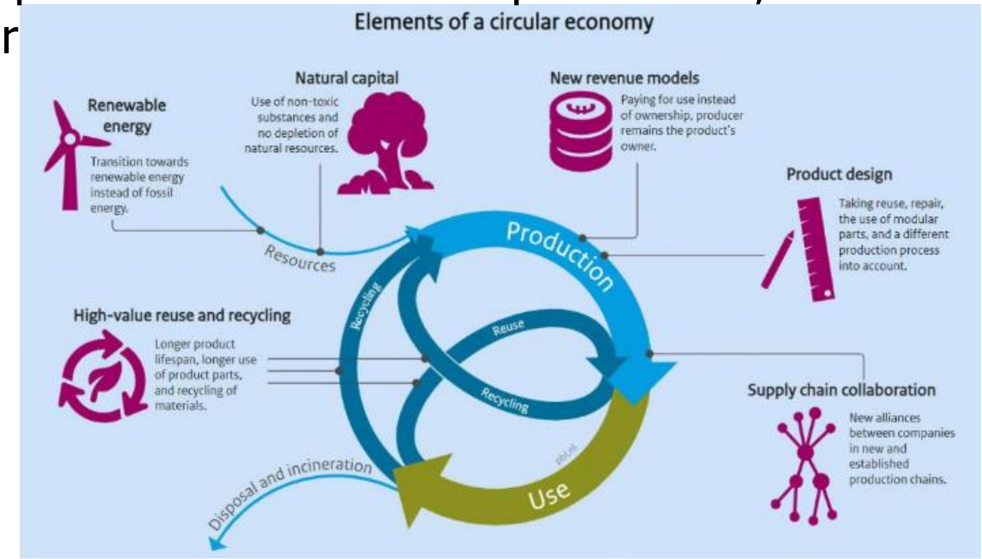
Presentation outline

- Circular economy: Definition & Principles
- From Eco-design and Life Cycle Assessment to Circular economy
- Eco-design strategies
- Life Cycle Assessment: Definition & Methodological stages
- Techno-economic analysis: Determination of the parameters
- Software and databases
- Introduction of the studied solar thermal collectors
- Detailed results for the studied Energy Systems
- Environmental and economic profile of the studied technologies
- Proposed Eco-design aspects for solar thermal systems
- Conclusions

Circular economy: Definition & Principles

The circular economy refers to an economic model whose objective is to produce goods and services in a sustainable way, by limiting the consumption and waste of resources (raw materials, water, energy) as well as the production of waste.
It is in rupture with the model of the linear economy, based on a take-make-consume-throw away pattern, by proposing to transform waste into recycled raw materials for product design or other uses.
This model fits directly into the more general framework of sustainable development and it is part of a global strategy that also uses, among other things, the principles of the green economy, industrial ecology, eco-design or the economy of functionality.
The circular economy encompasses a very large number of sectors of activity and can be broken down into 7 complementary patterns of production and consumption which, when combined, make sense and reinforce each other

1. Sustainable procurement
2. Eco design
3. Industrial and territorial ecology
4. Economics of functionality
5. Responsible consumption
6. Extending the duration of use
7. Recycling



A new path for designing Renewable Energy Systems

From Eco-design and LCA…

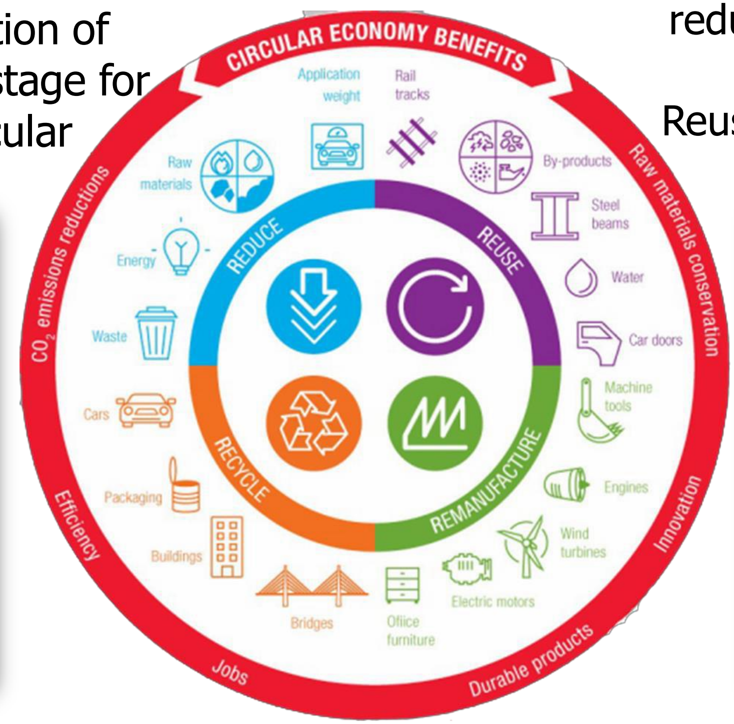
Eco-design has been defined as "the systematic integration of environmental considerations into product and process design" and its main advantage is that these considerations could be taken into proper account in the early stages of the design process.

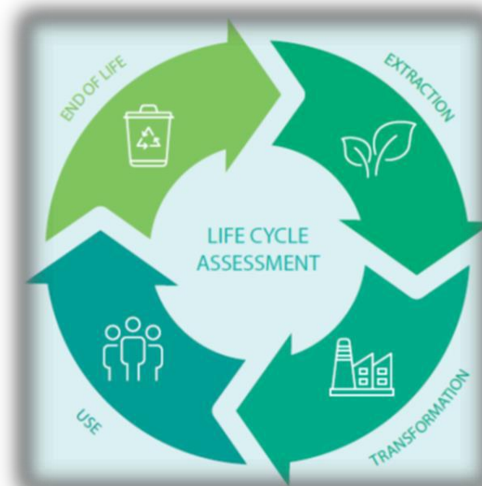
In addition to recycling materials in renewable technologies, the application of eco-design measures at the design stage for these systems can improve their circular economy performance.

…to Circular Economy

The linear "take-make-consume-dispose" economic system practiced within Renewable Energy Systems will inevitably undermine their sustainable status without an effective end-of-life management strategy.

Circular economy philosophy attempts to close the supply chain loop by reducing the need for virgin materials via the eco-design and "Reduce, Reuse, Recycle" principles to minimize waste throughout a product's life-cycle.

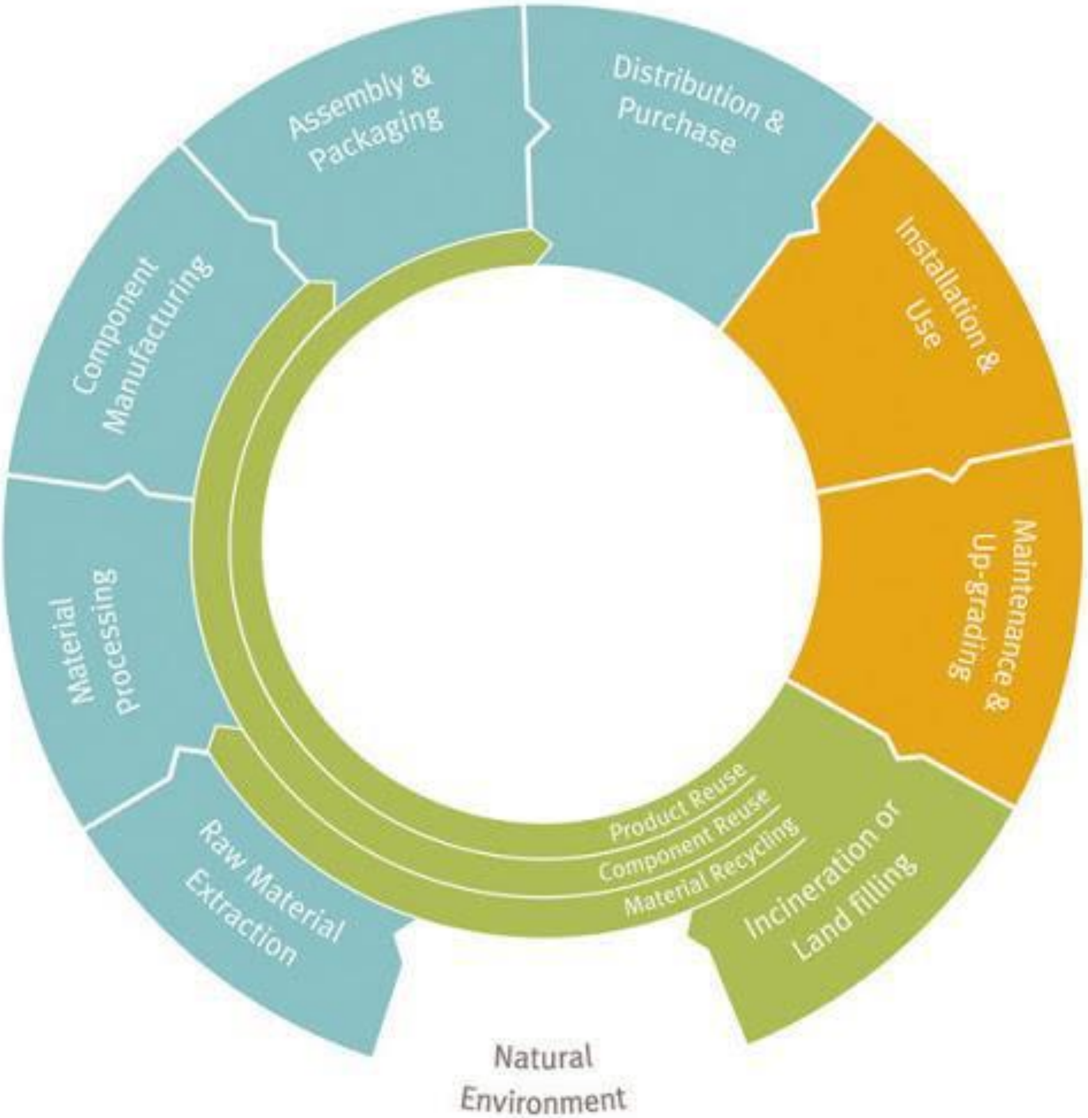




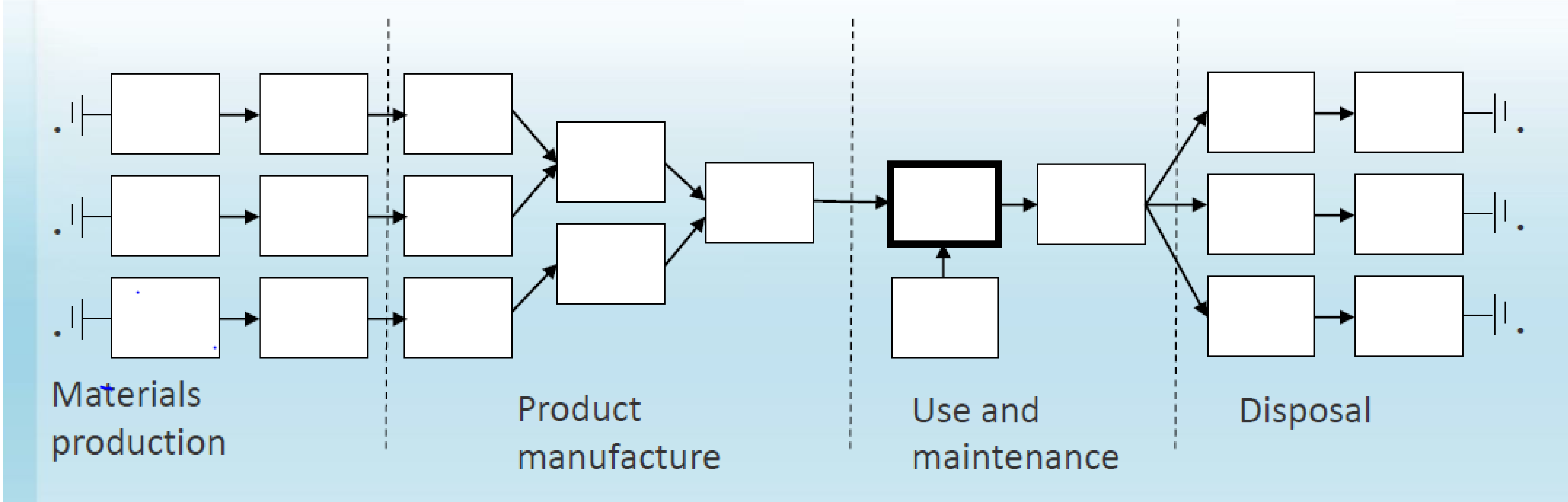
Eco-design

Eco-design strategies can be broadly categorized in the following eight groups, according to their main goal:

1. reduction of the number of different materials and selection of the most appropriate ones
2. reduction of environmental impact in the production phase
3. optimization of the distribution phase
4. reduction of environmental impact in the use phase
5. extension of the product's useful life span
6. simplification of product disassembly (design for disassembly)
7. design for reuse
8. design for recycling

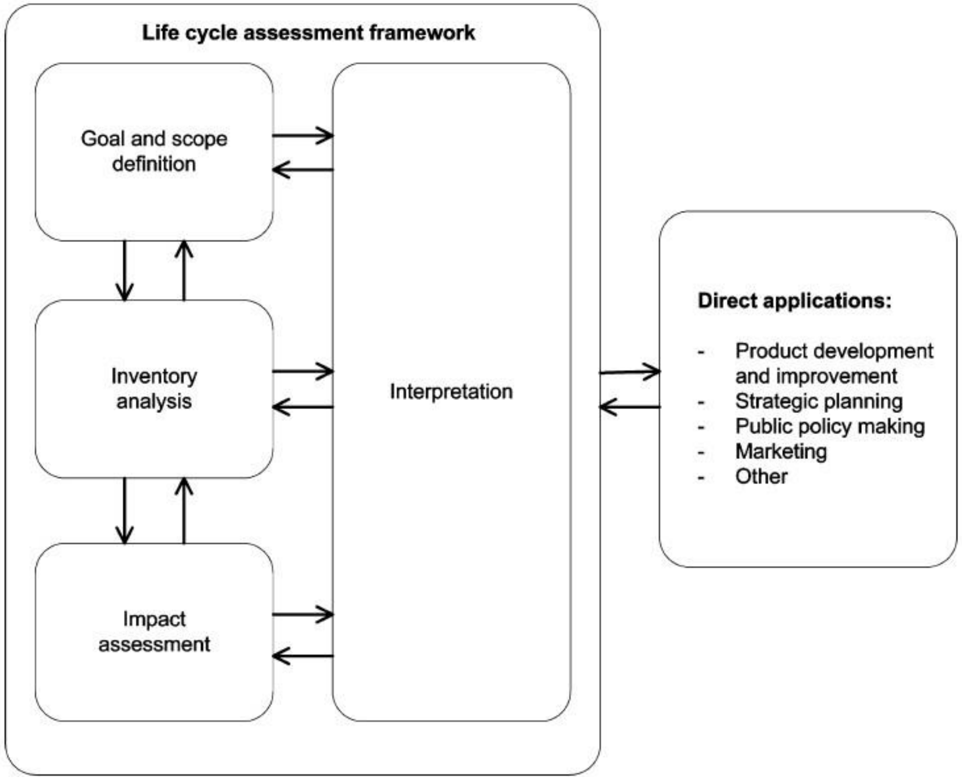


Life Cycle Assessment (LCA)



- 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.

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		

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

Annual hot water needs for the studied house

Hot water - Method 1

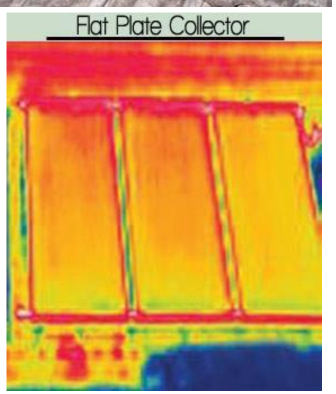
		Base case	Proposed case	Energy saved
☑ **Load type - calculator**		House		
Number of units	Occupant	4		
Occupancy rate	%	100%		
Daily hot water use - estimated	L/d	240		
Hot water use	L/d	180	180	
Temperature	°C	55	55	
Supply temperature method		Formula		
Water temperature - minimum	°C	15.6		
Water temperature - 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%

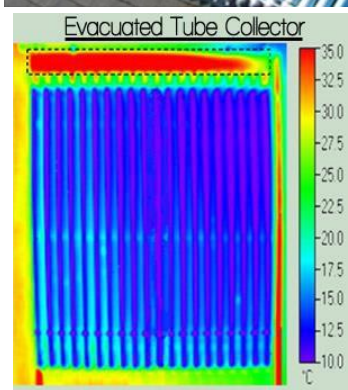
The energy needs for hot water supply for a typical family house with 4 occupants (taking as granted 100% occupancy rate and 24 operating hours per day) have been estimated to **2817**kWh/year. A typical auxiliary hot water heating system burning oil has been considered for backup.

Software and databases

- The environmental impacts of the studied solar thermal systems have been assessed and quantified through an LCA study implemented via SimaPro 9.1 incorporating the ecoinvent 3.6 database.
- The comparative techno-economic assessment of the installation of the two solar thermal collectors has been carried out through RETScreen.

Solar thermal systems



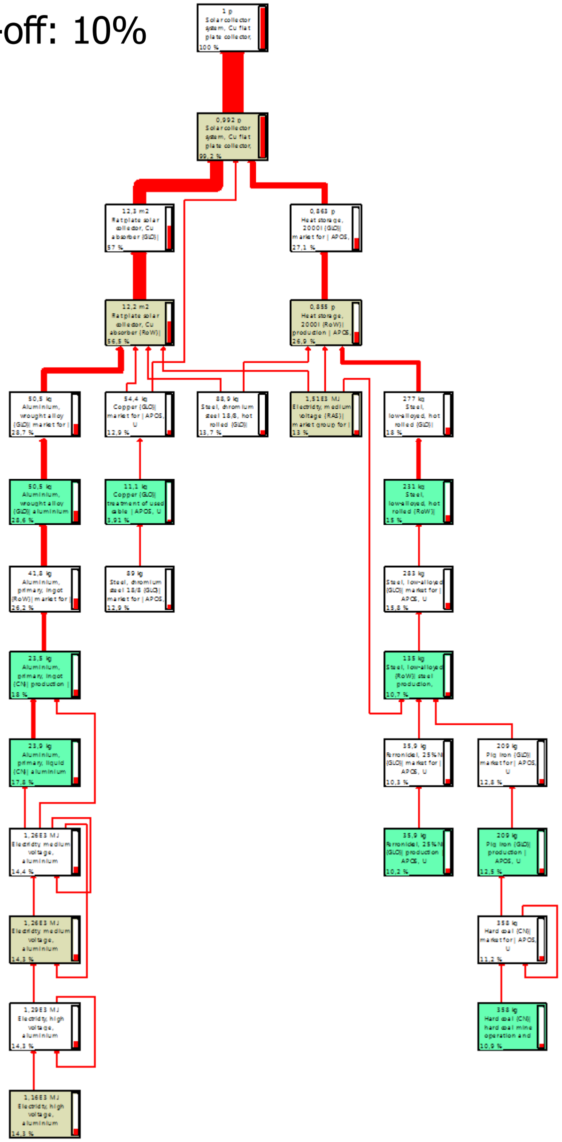


- ⇨ A **flat plate solar collector** consists of the dark absorber, the transparent cover, the heat transfer fluid containing the antifreeze and the water tank.
- ⇨ Heat transfer fluid circulates through tubes contained in the absorber. They are usually made of copper or aluminum and are painted with a special selective coating, which is much better in absorbing and retaining heat than ordinary colors.
- ⇨ A **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 as they are lightweight, compact and can be transported to the roof individually. In addition, the pipes can be replaced separately if damaged, avoiding the need to replace the entire collector.
- ⇨ Both systems are effective and durable with a life span of over fifteen years.

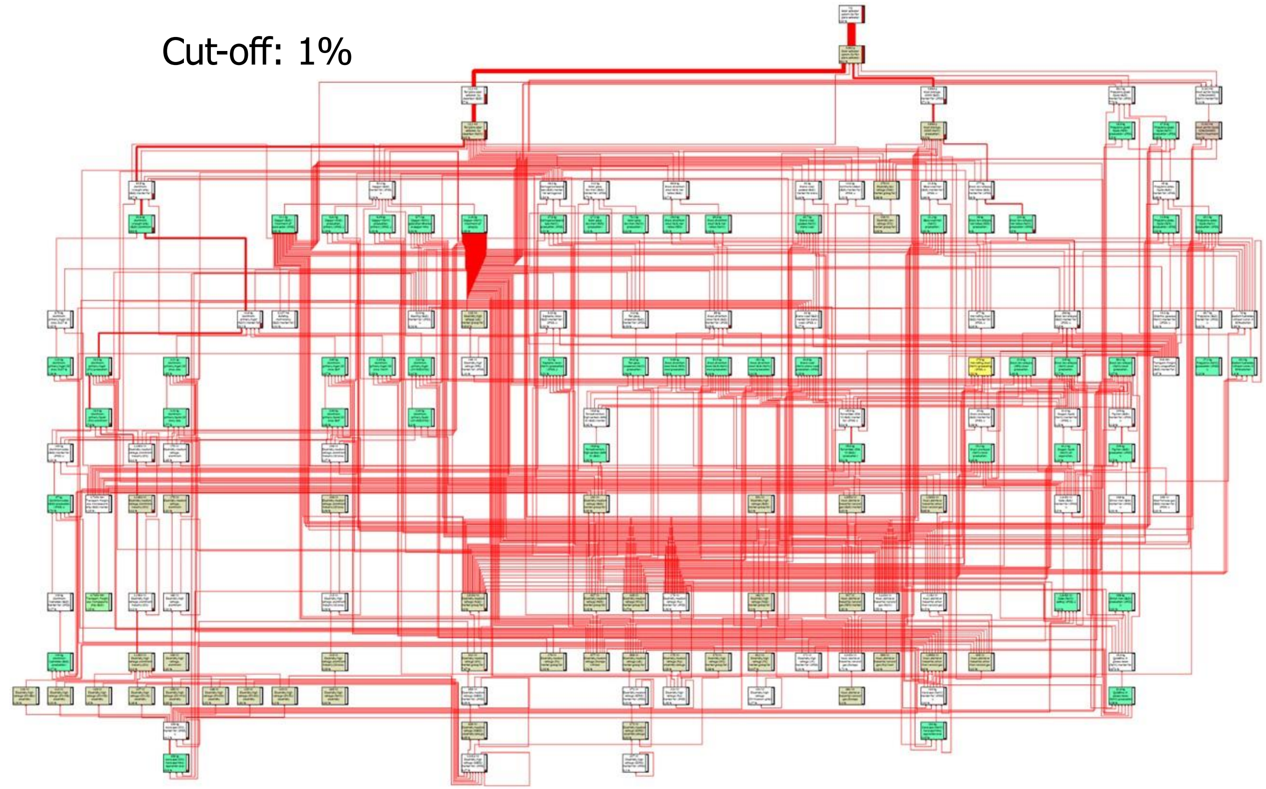
Detailed results for the studied Energy Systems

LCA process network (flat plate collector)

Cut-off: 10%

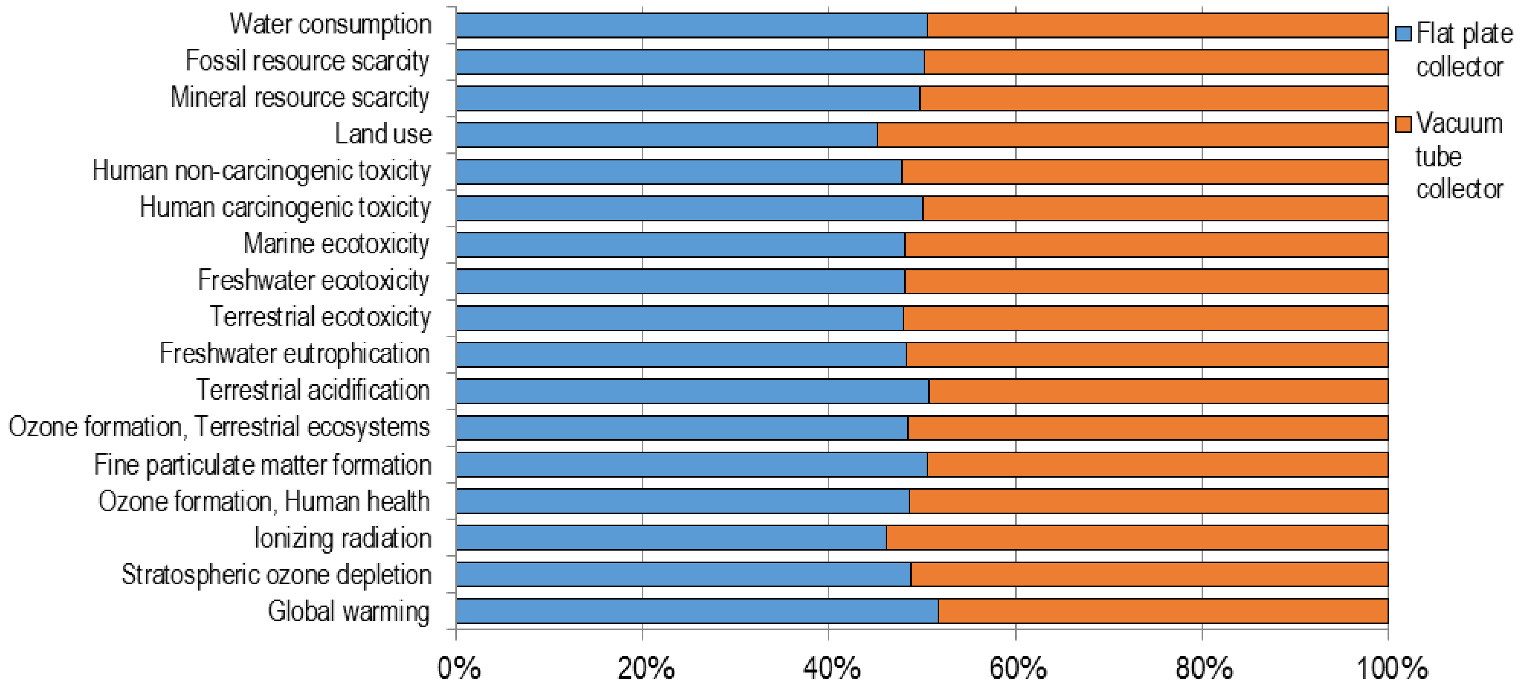


Cut-off: 1%



- 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.

LCIA results



- 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.

Technical assessment

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%

Economic assessment

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**

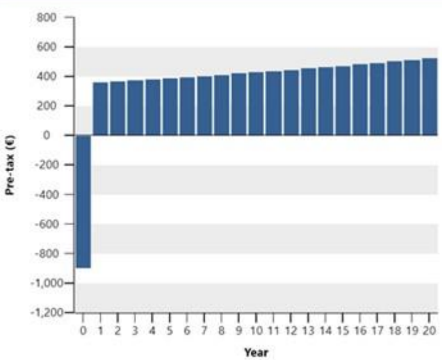
Financial viability

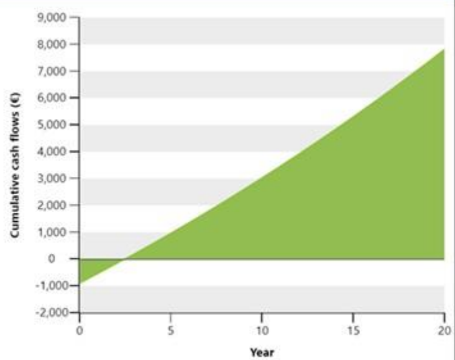
Pre-tax IRR - equity	%	41.8%
Pre-tax IRR - assets	%	41.8%
Simple payback	yr	2.6
Equity payback	yr	2.5
Net Present Value (NPV)	€	2,869
Annual life cycle savings	€/yr	314
Benefit-Cost (B-C) ratio		4.2
Debt service coverage		No debt
GHG reduction cost	€/tCO_2	-242

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

Yearly cash flows





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**

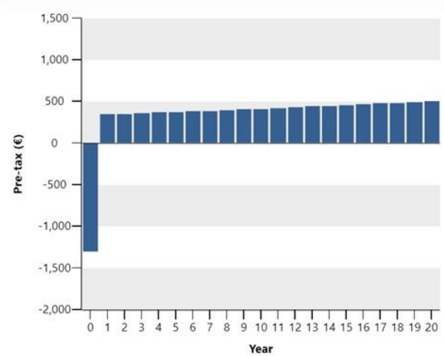
Financial viability

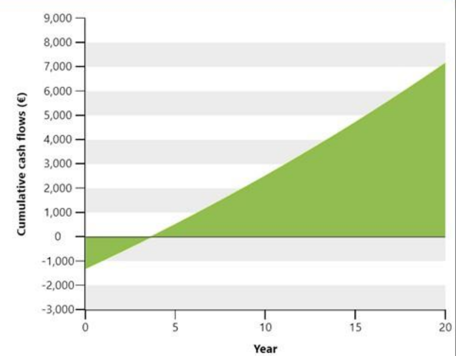
Pre-tax IRR - equity	%	28.5%
Pre-tax IRR - assets	%	28.5%
Simple payback	yr	3.8
Equity payback	yr	3.6
Net Present Value (NPV)	€	2,351
Annual life cycle savings	€/yr	258
Benefit-Cost (B-C) ratio		2.8
Debt service coverage		No debt
GHG reduction cost	€/tCO_2	-208

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

Yearly cash flows





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 €**.

Techno-economic assessment

Solar collector type	Aperture area [m²]	F_rUL [(W/m²)/°C]	Cost [€]	Total energy saved [kWh]	Total energy saved per aperture area [kWh/m²]	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	3.6

- As already mentioned the thermal losses coefficient (F_rU_L) 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 the thermal losses do not play an important role for 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 the weather conditions in Crete (high intensity solar radiation for extended time periods and with increased ambient temperatures throughout the year) which 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.
- The economic viability of the two systems is obvious: the simple payback period is **2.6** and **3.6** 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.

Eco-design in Solar thermal systems

- Eco-design aspects for solar thermal systems focus on new designs that allow the devices to be disassembled, thus improving their recycling potential.
- With a circular economy in mind, systems can have various improvements, i.e. they can be designed to allow the absorber plate to be detached from the storage tank.
- The storage tank can be made of stainless steel, thus improving the collector's recycling potential (as steel and aluminium can be cleanly separated and reused).

Part	Material	Recycle	Eco design
Storage tank	Stainless steel	Yes	Yes
Heat exchanger	Copper or Steel	Yes	Important part of the environmental impacts are associated to copper, leading to a replacement with steel
Glazing	Glass	Yes	Use of Transparent Insulating Materials
Absorber plate	Aluminium	Yes	Yes
Insulation	PolyUrethane or Rockwool	Yes	Use thinner layer
Casing	Galvanized steel sheet for the back	Yes	Yes
Tubes	Copper	Yes	Replace copper with steel
Collector frame	Aluminum profiles for the sides	Yes	Increase of the recycled aluminum percentage

Conclusions

The comparison of flat plate and vacuum tube solar thermal collectors aimed at stressing the advantages and disadvantages of both technologies.

- For the **environmental profile** of the studied systems the production stage of the collector component contributed the most important part of the environmental impacts in the life cycle for both collectors followed by the production of the tank. The two technologies exhibited similar environmental impacts in most categories, but the vacuum tube collector had highest values in most cases.
- For the **energy profile** both systems could cover more than half of the annual hot water needs for a family house with 4 occupants, thus the technical advantage of the vacuum tube collector, being practically unaffected by the variations in ambient temperature, was not reflected in its final energy outcome mainly due to the favourable weather conditions in the selected installation location which made the flat plate collector equally efficient.
- For the **economic profile** the purchase cost of the vacuum tube system is almost 45% higher, thus stressing the fact that for typical installations in Crete the flat plate collector should be the principal option. In addition, the economic viability of both technologies was proved as the simple payback period estimated to be 2.6 and 3.6 years for the flat plate and the vacuum tube system respectively.

Thank you for your interest

For any further questions please contact us at:

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