



# ***Solar Air-Conditioning Systems***

*in small - medium scale applications*

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## The problem

- **Ozone layer depletion**

CO<sub>2</sub> higher now than in last 400,000 years

CO<sub>2</sub> emissions are expected to increase 20-fold from 1990 to 2010, only in the EU

- **IPCC predicts temperature rise of 1.5 - 5.8 degrees**

Humans: 150,000 deaths directly attributable to climate change in 2000

Climatic zones shifting 7 times quicker than plants can follow

- **New directives on air quality**

2008/50/EC, '*Ambient air quality and cleaner air for Europe*'

2008/1/EC, '*Integrated pollution prevention and control*'

- **Inefficient conventional a/c units**

- **VCS** operate at a temperature colder than the supply air dew-point temperature, so **the air is overcooled** and needs reheating before entering indoors

- **Energy consumption** in commercial and residential buildings: **40% of Europe's energy bill**

- **Global increase in air-conditioning demand**



Global sales of air conditioning units, 2000-2008 (Millions)

	2000	2001	2002	2003	2004	2005	2006	2007	2008
Japan	7.791	8.367	7.546	7.307	7.679	7.500	7.500	7.500	7.500
Asia	13.897	16.637	17.761	23.650	26.430	28.312	30.340	32.524	34.881
Europe	1.673	1.730	1.804	2.218	2.366	2.515	2.604	2.660	2.717
M. East	2.907	2.918	3.412	4.359	4.799	5.087	5.382	5.694	6.118
N. America	12.322	11.894	12.910	13.075	12.876	12.881	12.889	12.897	12.905
S. America	2.109	1.939	2.036	2.243	2.331	2.418	2.473	2.530	2.592
Africa	664	758	700	814	850	885	915	944	978
Australia	512	593	671	712	815	825	868	913	963
<b>Total</b>	<b>41.874</b>	<b>44.834</b>	<b>46.840</b>	<b>54.379</b>	<b>58.147</b>	<b>60.422</b>	<b>62.970</b>	<b>65.663</b>	<b>68.654</b>

JRAIA (Japan Refrigeration and Air Conditioning Industry Association)

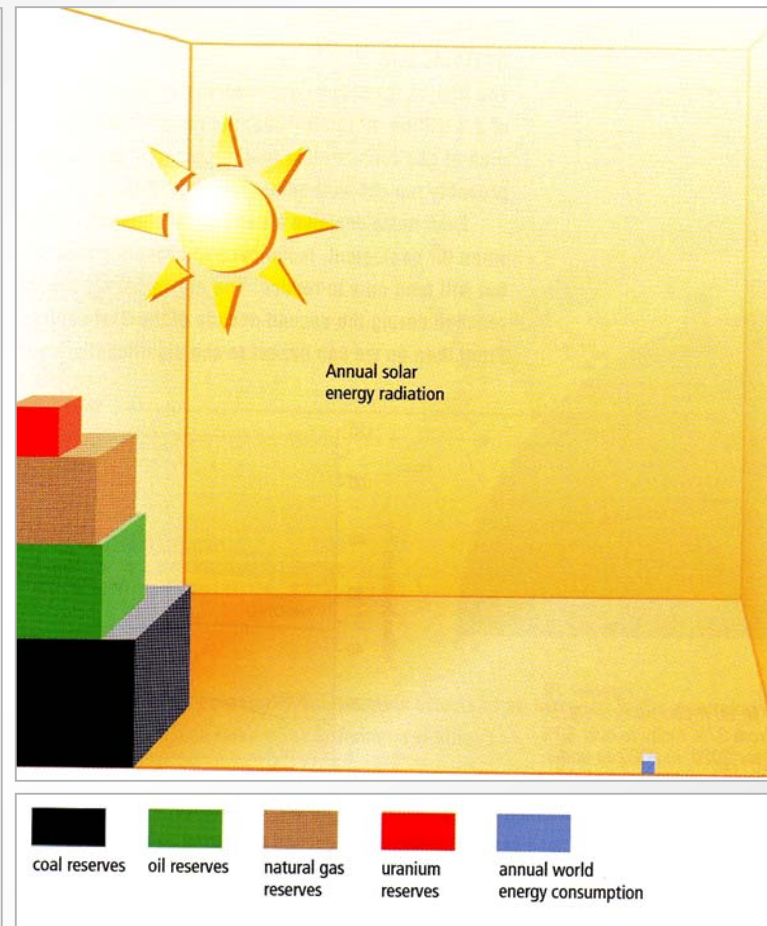
- Higher living / working standards
- Adverse outdoor conditions in urban environments
- Reduced prices of air-conditioning units
- Installed a/c has increased 5-fold in the last 20 years in Europe
- Total a/c floor space: 30 million m<sup>2</sup> in 1980, over 150 million m<sup>2</sup> in 2000.
- Annual energy use of room a/c was 6 TJ in 1990, estimated 160 TJ in 2010.

***We need an a/c system that controls temperature and provides air of high quality, with high efficiency and low CO<sub>2</sub> emissions!***

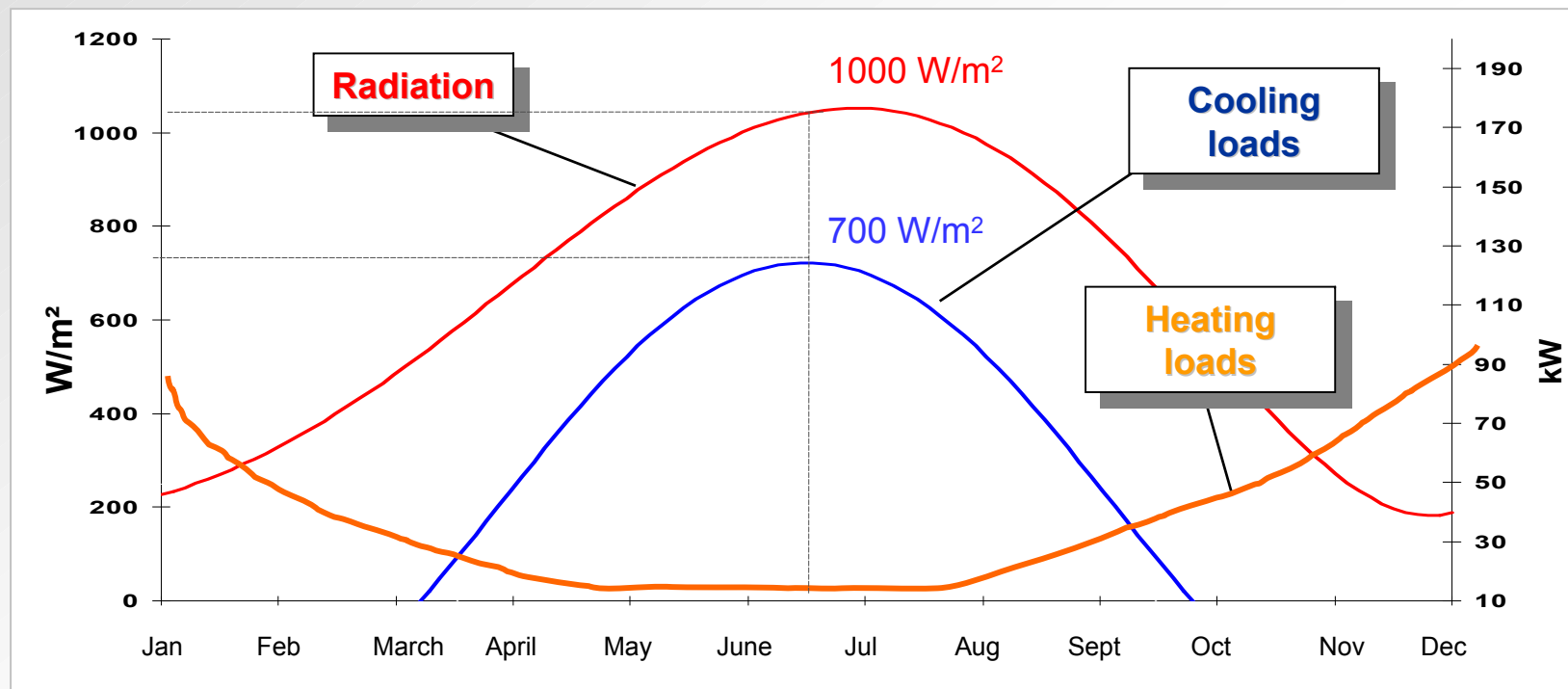


## The solution : Solar-driven air-conditioning

- **Radiation** supply from sun carries a **5 billion year guarantee**
- Annually, **the sun provides  $1.5 \times 10^{18}$  kWh**, that is more than 10,000 times the energy that human race needs.



Source: *Planning & Installing Solar Thermal Systems: A guide for installers, architects & engineers*, EarthScan publications

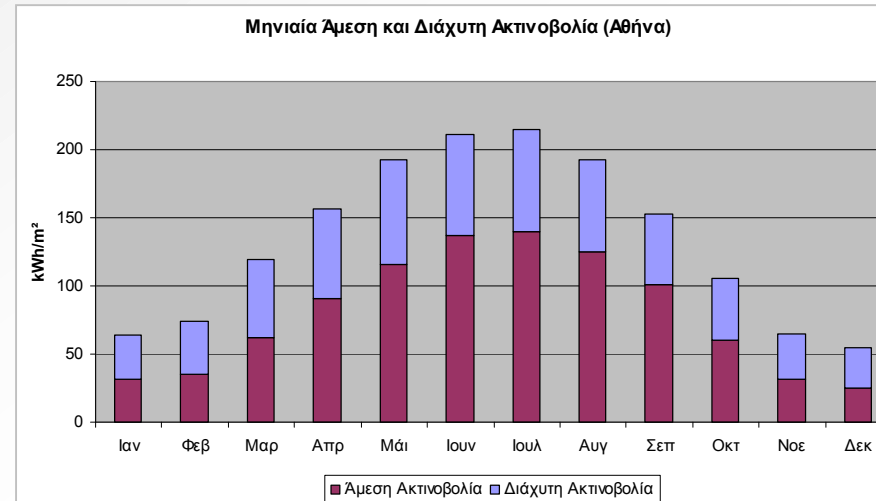


***Solar radiation is in tune with air conditioning demand***

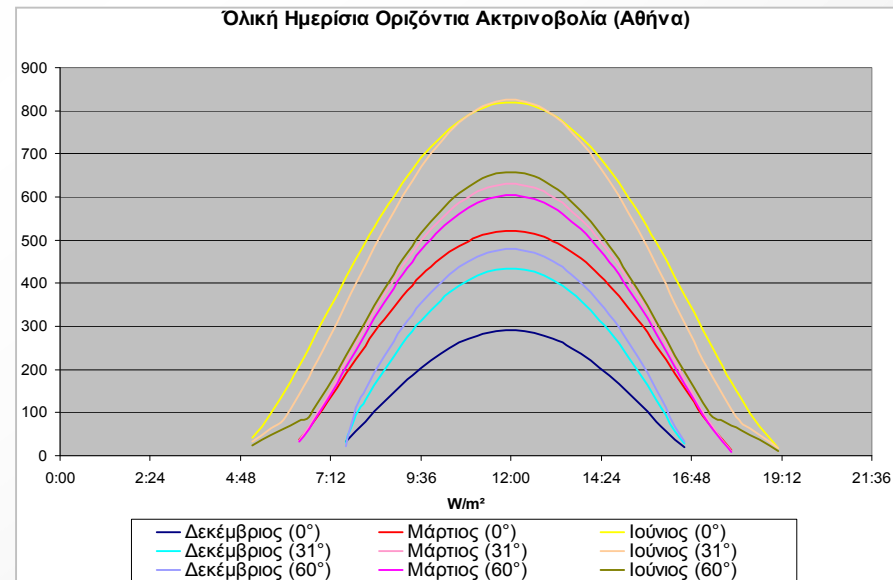
Source : TECSOL for SOLAIR project



- Annual solar irradiance (sum of direct and diffuse) in Greece is approximately **1,600 kWh/m<sup>2</sup>**.
- This amount of energy, corresponds to **160 lt oil**.



- Daily solar irradiance for 3 representative dates (in winter, summer and spring) is shown in the next diagram.
- The area that receives the biggest amount of radiation has an inclination of **60° in December** and **0° in June**.



Source : CRES, PVGIS

Optimum collector angle: depends on the geographical location and the system's type of use.

- **Winter use:** geographical latitude of area + 15°
- **Summer use:** geographical latitude of area - 15°
- **Annual use:** collector angle = **geographical latitude**

RESULTS OF INCIDENT RADIATION ON COLLECTORS (FROM TSOL)

Place: Athens

Azimuth: 0

		G Inclined, Specific[kWh/m²] according to collectors inclination (in degrees °)																
From:	To:	0	10	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
1/ 1/	1/ 2/	66	80	91	96	100	104	107	109	111	112	113	112	111	109	107	104	100
1/ 2/	1/ 3/	75	84	91	93	96	97	99	99	99	99	98	96	94	91	88	84	80
1/ 3/	1/ 4/	104	112	116	118	119	119	119	118	116	114	111	108	104	99	94	89	83
1/ 4/	1/ 5/	146	151	152	152	151	149	147	143	139	134	129	123	116	108	101	92	84
1/ 5/	1/ 6/	182	183	181	178	175	170	165	159	153	145	137	128	119	109	100	90	79
1/ 6/	1/ 7/	200	200	195	191	185	180	173	166	158	149	139	128	118	108	96	85	75
1/ 7/	1/ 8/	213	214	210	205	199	194	187	180	171	162	151	139	128	117	105	91	80
1/ 8/	1/ 9/	200	206	206	204	202	199	194	188	182	174	165	155	144	132	121	109	96
1/ 9/	1/10/	156	168	176	179	180	181	180	178	175	171	166	161	154	146	138	128	118
1/10/	1/11/	106	120	130	134	138	140	142	143	142	142	140	137	134	130	125	119	113
1/11/	1/12/	66	77	86	90	94	96	99	100	101	102	102	101	99	97	95	92	88
1/12/	1/ 1/	53	63	72	76	79	82	85	87	88	89	89	89	88	87	85	83	80
<b>Sum YEAR</b>		<b>1567</b>	<b>1658</b>	<b>1706</b>	<b>1716</b>	<b>1718</b>	<b>1711</b>	<b>1697</b>	<b>1670</b>	<b>1635</b>	<b>1593</b>	<b>1540</b>	<b>1477</b>	<b>1409</b>	<b>1334</b>	<b>1252</b>	<b>1165</b>	<b>1075</b>
<b>hotels season: 1/4 to 1/11</b>		<b>1203</b>	<b>1242</b>	<b>1250</b>	<b>1243</b>	<b>1230</b>	<b>1213</b>	<b>1188</b>	<b>1157</b>	<b>1120</b>	<b>1077</b>	<b>1027</b>	<b>971</b>	<b>913</b>	<b>850</b>	<b>784</b>	<b>714</b>	<b>645</b>
<b>heating season: 1/11 to 1/4</b>		<b>364</b>	<b>416</b>	<b>456</b>	<b>473</b>	<b>488</b>	<b>498</b>	<b>509</b>	<b>513</b>	<b>515</b>	<b>516</b>	<b>513</b>	<b>506</b>	<b>496</b>	<b>484</b>	<b>468</b>	<b>450</b>	<b>430</b>
"winter": 1/12 to 1/3		194	227	254	265	275	283	291	295	298	300	300	297	293	287	280	270	260

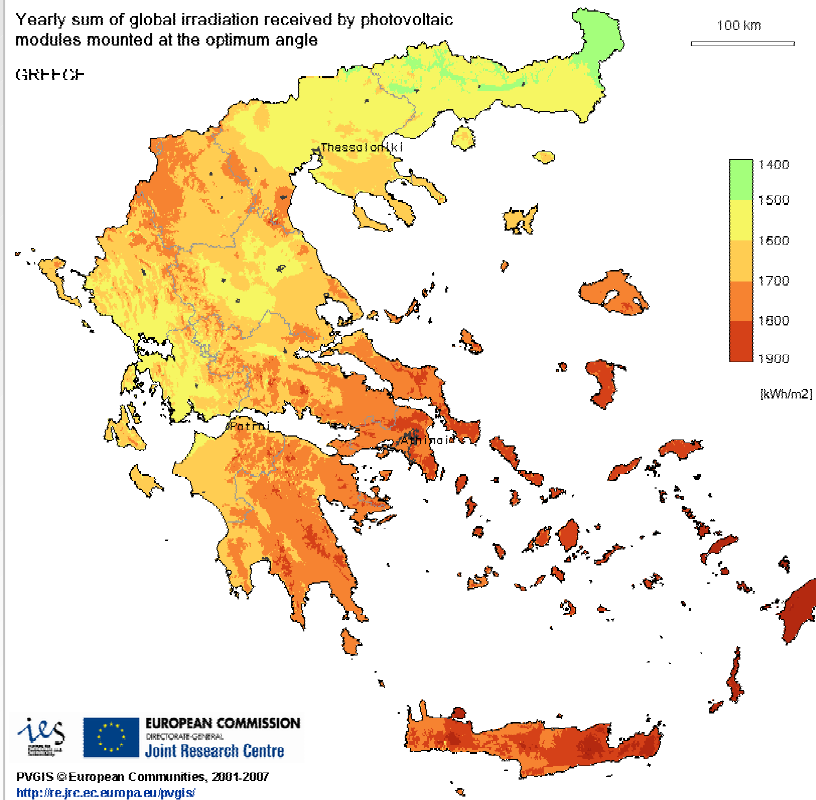
Source : T-SOL

## Energy yield

Optimum angle: 1700-1800 kWh/m<sup>2</sup>

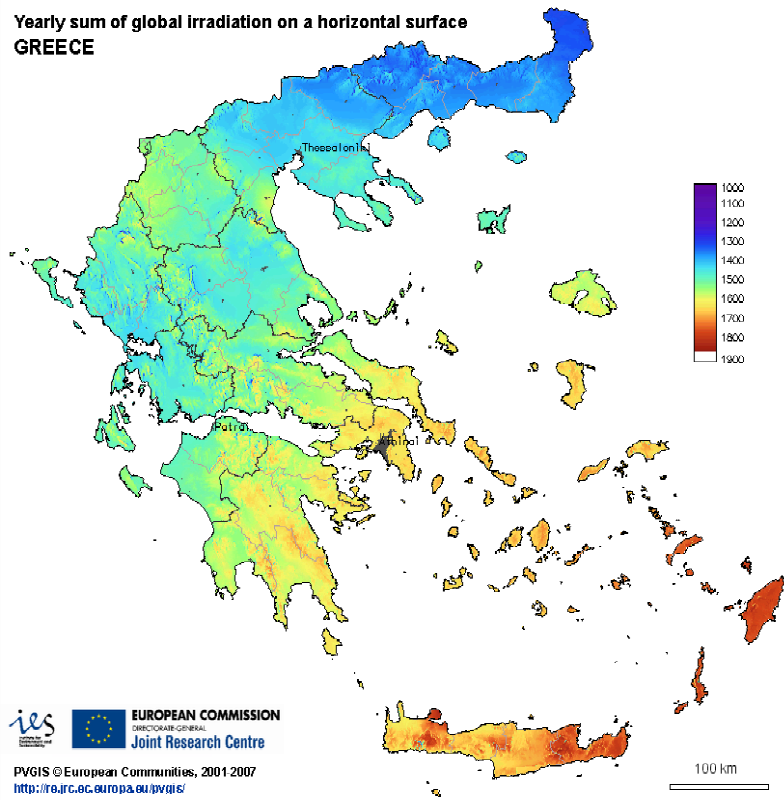
Yearly sum of global irradiation received by photovoltaic modules mounted at the optimum angle

GREECE



Horizontal surface: 1300-1400 kWh/m<sup>2</sup>

Yearly sum of global irradiation on a horizontal surface  
GREECE



Source : PVGIS



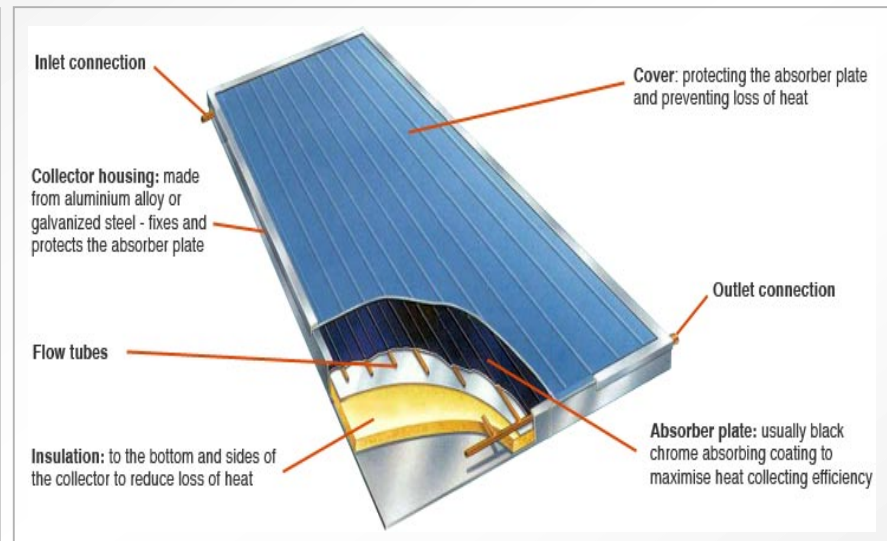
## Standard flat plate collectors

### Properties

- Middle cost: more expensive than unglazed, but cheaper than vacuum
- Higher operation temperature
- Thermal insulation on back & edges
- Fragile, heavier: 20-32 kg/m<sup>2</sup>
- Absorber: black paint or spectral-selective coating (black chrome, black nickel, blue titanium)
- Spectral-selective coating: conversion of short-wave solar radiation into heat (light absorption capacity) is optimized, while thermal emissions are kept low. Absorption rate: 90-95%, emission rate 5-15%
- Stagnation temperature: 160-200°C

### Applications

- Space heating
- Solar air conditioning (selective coating)



*Planning & Installing Solar Thermal Systems: A guide for installers, architects & engineers, EarthScan publications*

## Vacuum collectors

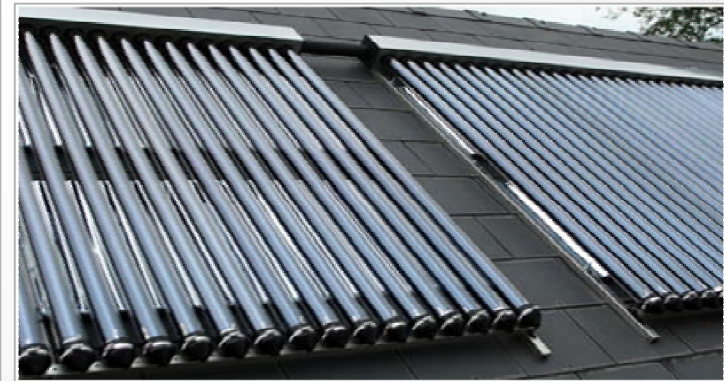
### Properties

- High cost
- Minimal convection thermal losses (tube pressure  $< 10^{-5}$  bar)
- Low radiation losses
- High efficiency, even with low radiation
- Low weight
- Average annual efficiency 45-50% (with  $1000\text{kWh/m}^2$  irradiation, the energy yield is  $450\text{-}500\text{kWh/m}^2\text{a}$ )
- Stagnation temperature:  $200\text{-}350^\circ\text{C}$

### Applications

- Solar air conditioning
- Industrial applications (steam generation)

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## Vacuum types

- **Direct-flow:** Internal U-tube, South-oriented.

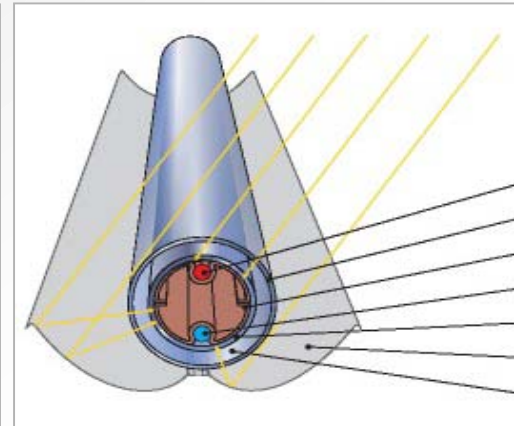
**Concentrated:** Double tube (external tube: absorber surface, internal tube: U-type), 2 external reflector surfaces

### - Heat-pipe:

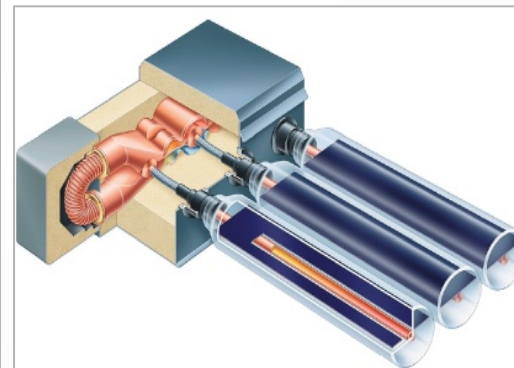
Horizontal absorber area placed inside a vacuum tube. The tube is connected to an evacuated heat pipe with a solution inside. The solution evaporates ( $T_{\text{evaporation}} = 250^{\circ}\text{C}$ ) and its heat is transferred through a heat exchanger in the medium.

**Dry connection:** the heat transfer takes place from the condenser via the tube wall to the medium, so defective tubes are replaced without emptying the solar circuit)

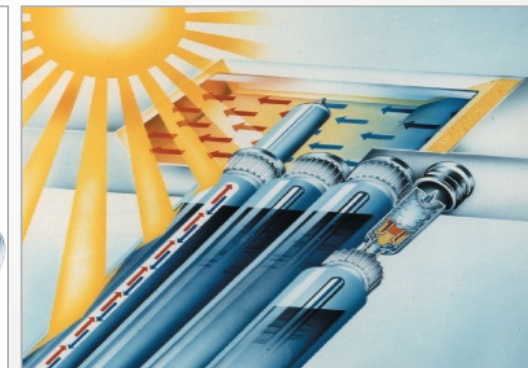
**Wet connection:** the condenser is immersed in the medium, so defective tubes are replaced by emptying the solar circuit.



Concentrated vacuum collector



Cross section of heat pipe dry connection



Cross section of heat pipe wet connection

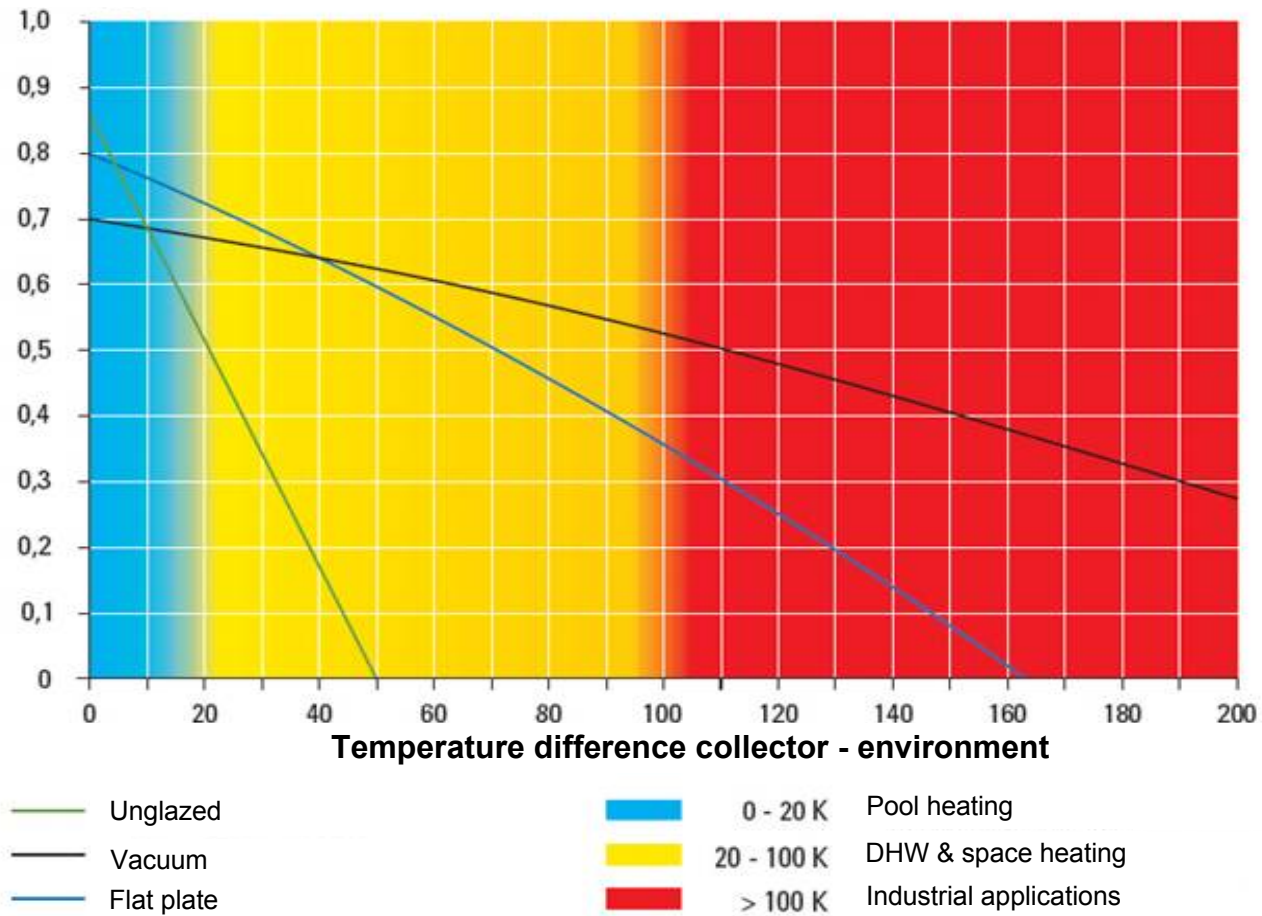
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## Collectors comparison

Collector type	Application	Performance (kWh/m <sup>2</sup> a)
Unglazed	Pool heating	300
Flat plate (black paint)	Pool heating, Hot water	650
Flat plate (selective coating)	Hot water, space heating, solar a/c	700
Vacuum	Solar a/c, industry	850



## Performance



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## Solar-driven air-conditioning systems

### Systems

#### ▪ Open cycle DEC

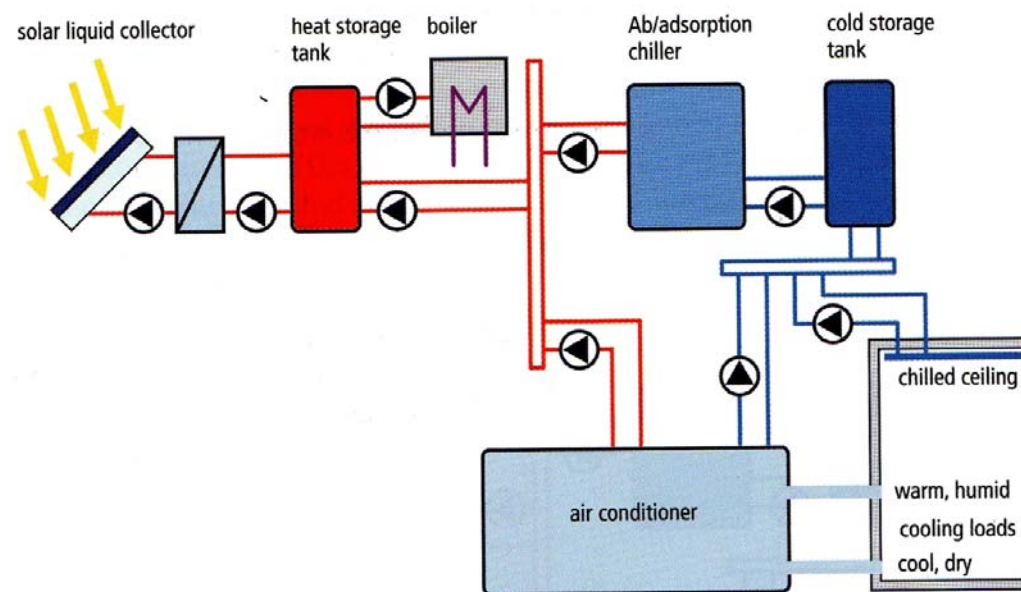
Production of air conditioned air  
Dehumidification and evaporative cooling

#### ▪ Closed cycle

Production of chilled water for space cooling through fan coil, chilled ceiling, floor heating

Absorption (liquid)





Adsorption (solid)



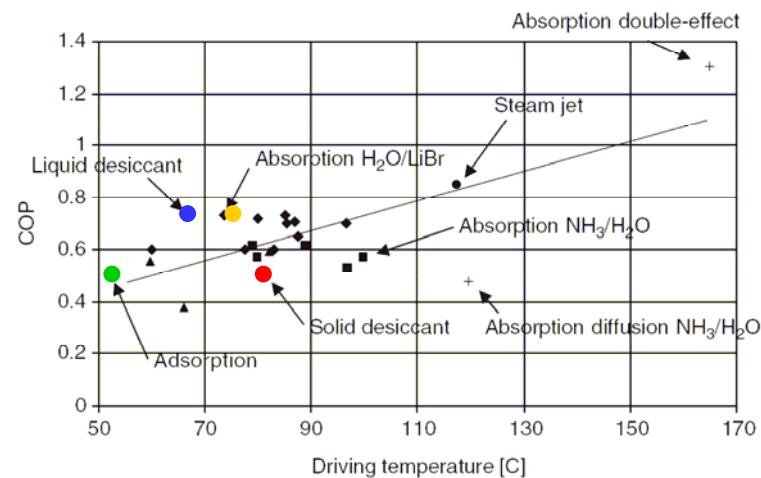
### Characteristics

- ✓ Air conditioning load in tune with the solar radiation
- ✓ Solar systems can be integrated in existing air-conditioning units (fan coils, floor heating systems)
- ✗ Small scale solar a/c systems: under research
- ✗ Small scale chillers (<30kW): High initial cost, 2,000 €/kW.



Method	Closed cycle		Open cycle	
Refrigerant cycle	Closed refrigerant cycle		Refrigerant (water) is in contact to the atmosphere	
Principle	Chilled water		Dehumidification of air and evaporative cooling	
Phase of sorbent	solid	liquid	solid	liquid
				
Typical material pairs	water - silica gel	water - lithium bromide ammonia - water	water - silica gel, water - lithium chloride	water - calcium chloride, water - lithium chloride
Market available technology	Adsorption chiller	Absorption chiller	Desiccant cooling	Close to market introduction
Typical cooling capacity (kW cold)	50 – 430 kW	15 kW – 5 MW	20 kW – 350 kW (per module)	
Typical COP	0.5 – 0.7	0.6 – 0.75 (single effect)	0.5 – >1	> 1
Driving temperature	60 – 90 °C	80 – 110 °C	45 – 95 °C	45 – 70 °C
Solar collectors	Vacuum tubes, flat plate collectors	Vacuum tubes	Flat plate collectors, solar air collectors	Flat plate collectors, solar air collectors

Source : EU Altener Project Climasol



Efficiency – Operational temperature, 2007

#### Open systems

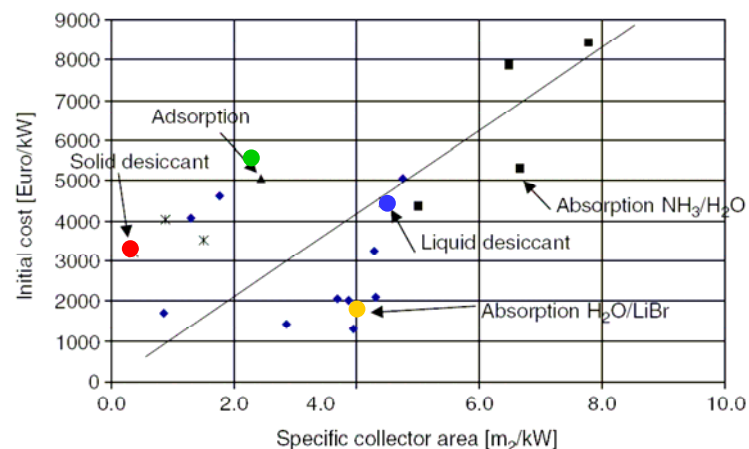
Liquid DEC:  $T = 60^\circ\text{C}$ ,  $\text{COP} = 0.7$

Solid DEC:  $T = 80^\circ\text{C}$ ,  $\text{COP} = 0.5$

#### Closed systems

Absorption:  $T = 75^\circ\text{C}$ ,  $\text{COP} = 0.7$

Adsorption:  $T = 55^\circ\text{C}$ ,  $\text{COP} = 0.5$



Initial cost – Collector area needed, 2007.

#### Open systems

Liquid DEC: 4500 €/kW, 5 m<sup>2</sup>/kW

Solid DEC: 3500 €/kW, 0.5 m<sup>2</sup>/kW

#### Closed systems

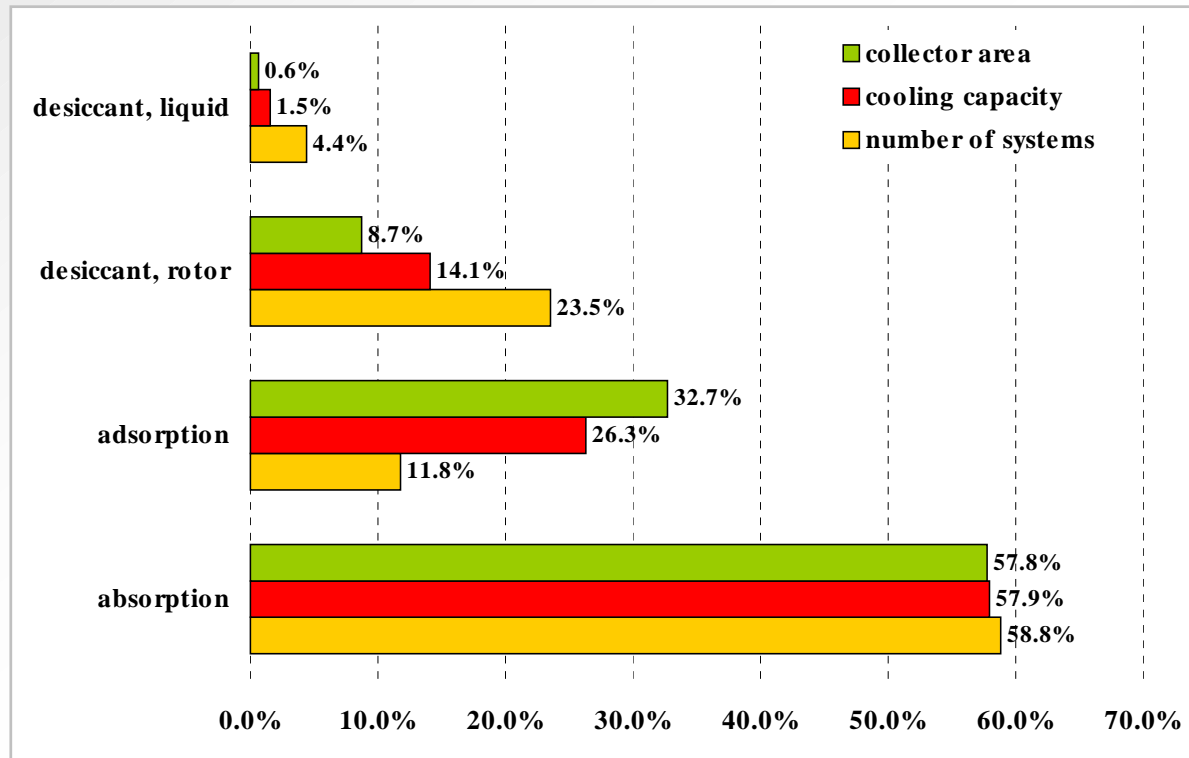
Absorption: 2000 €/kW, 4 m<sup>2</sup>/kW

Adsorption: 5500 €/kW, 2.5 m<sup>2</sup>/kW

Source : CA Balaras, G Grossman, HM Henning, *Solar Air-Conditioning in Europe - an overview*, Renewable Energy & Sustainable Energy Reviews, 11, 2007, 299-314

## Solar Cooling Systems installed in Europe

- Absorption: 58%
- Solid DEC: 23%
- Adsorption: 12%
- Liquid DEC: 4%



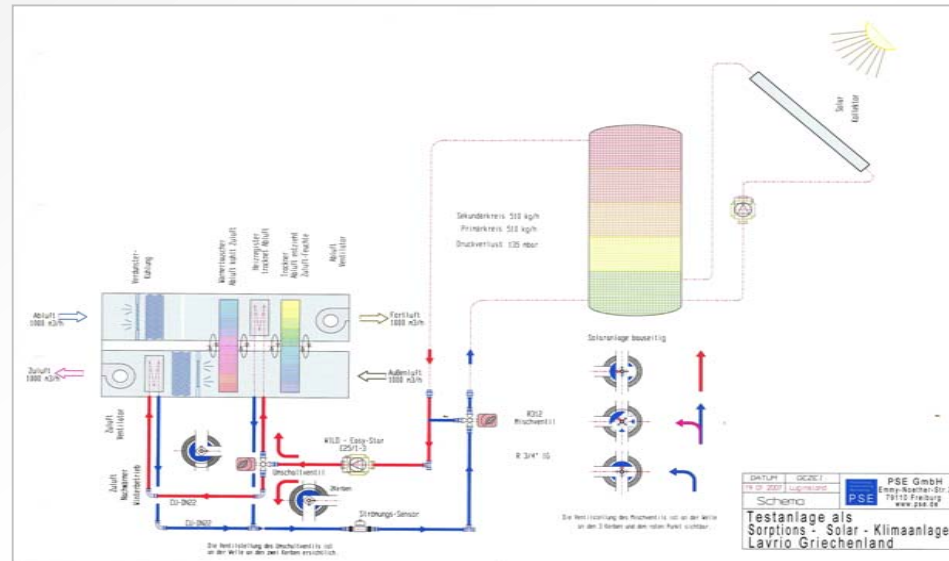
Source : HM Henning, *Solar Assisted air conditioning of buildings – an overview*, Applied Thermal Engineering, 27, 2007, 1734-1749.

## CRES, demo project, Lavrio, Athens

PENA, Lavrio  
Solar cooling **Solid DEC system**  
Demo & research application for CRES

In operation since	2007
Air conditioned area	84m <sup>2</sup>
Collector type	10 m <sup>2</sup> , Calpak flat-plate
Collector fluid	water-glycol
Operation temperature	60°C
Nominal air flow rate	1100 m <sup>3</sup> /h
Min. air volume flow rate	373 m <sup>3</sup> /h
Desiccant cooling system	solid LiCl
Brand of desiccant unit	Klingenburg

Source : CRES

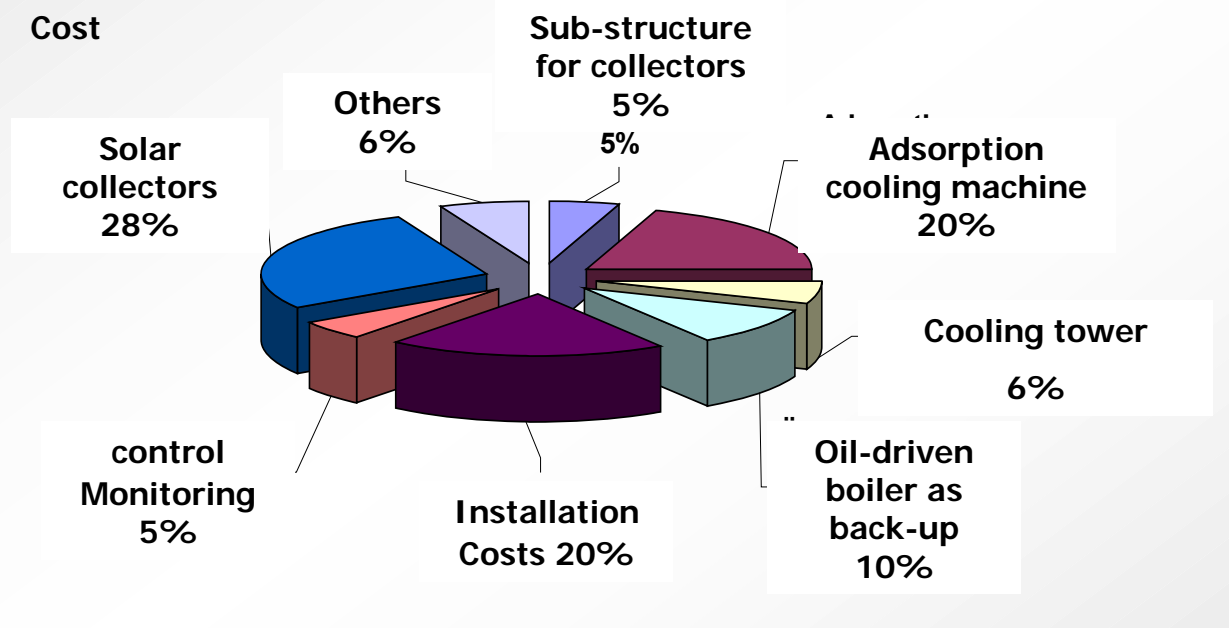


Solar cooling of a production site for cosmetics

- In operation since 1999
- One of the largest installations in the world
- 2,700 m<sup>2</sup> flat plate collectors (SOLE)
- 2 **adsorption cooling** machines, with 350 kW cooling power each
- 3 compression cooling machines with 350 kW air cooling and fan-coils
- Concept: economisation of electricity (Power and Work)

Source : CRES

Cost





## Rethimno Village Hotel, Crete

In operation since 20/08/00

Solar air-conditioning system, fan coils

Air-conditioned area 1000 m<sup>2</sup>

450m<sup>2</sup> flat plate collectors (SOLE)

**Absorption chiller** LiBr, 105 kW<sub>c</sub>

Performance: COP<sub>thermal</sub> = 0.6,

COP<sub>electrical</sub> = 0.52

Initial cost: 146,000 € (2000)

Annual electrical energy savings:

70,000 kWh (7,000€)

Annual oil savings: 20,000 lt (8,000€)

Payback in 10 years, without incentives.

870,000 kg less CO<sub>2</sub> annually

Source : SOLE





## Conclusions

- **Solar Cooling is not yet widespread** in Greece
  - 8% of the solar thermal market
  - lack of real incentives
- However, there is **large growth potential**, because
  - only 25% of the buildings are equipped with a solar thermal system (>90% of the owners are satisfied)
  - steady increase in demand for a/c units



### **Law modernization**

solar cooling system project study compulsory for every large building

### **Financial incentives**

to cover part of investment & construction costs

*Thank you for your attention!*



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