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Fakulteta za strojništvo
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INTELLIGENT ENERGY EUROPE
FOR A SUSTAINABLE FUTURE

IDES-EDU modul **Energy production**

Lecture #8 **Solar assisted cooling**

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Presentation is based among others on results and deliverables of SOLAIR project **EIE/06/034/SI2.446612 and Guidelines** prepared by Edo Wiemken form Fraunhofer ISE in collaboration with Sašo Medved, University of Ljubljana, Slovenia; Maria João Carvalho, INETI, Portugal. Use of SOLAIR materials is strongly recommended..

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What is solar assisted cooling

- It is quite often that during summer time surplus of heat emerge in buildings, like waste heat from cogeneration or surplus heat from solar thermal system.
- It is possible to convert those heat into cold using so called sorption chillers. In this case electrical driven compressor is replaced by pump with much lower electricity consumption. This reduce cooling cost and emissions of greenhouse gases.
- Sorption chillers produce, similar to compressor chillers, cooling water with temperature in range of 5°C to 12°C. Cooling water is than pumped to heat exchangers called “fan-coils” (->) to cool the space.

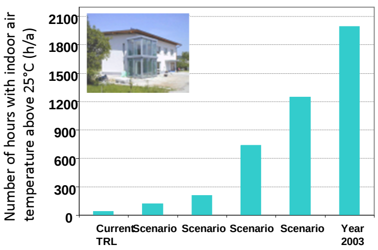
What is solar assisted cooling

- Evaporative cooling, presented in lecture #9, is efficient if local climate is dry, otherwise additional moistening of fresh supply air could cause unpleasant indoor comfort.
- This can be avoid if water vapour is dispossessed from fresh supply air by sorption process in so called desiccant-evaporative cooling system or DEC systems. Additional heat is that needed for desorption of water vapour from sorption matter.
- DEC system supply buildings via ventilation or air-conditioning system with fresh air having temperature low as 18 to 20°C and with relative humidity lower then 60%.
- Hot water or steam produced from fossil fuels or district heat can be used as driven heat, but lecture will focus on sorption or DEC cooling system that operates using heat produced by thermal solar systems.

mporatnce of buildings cooling will increase in the future

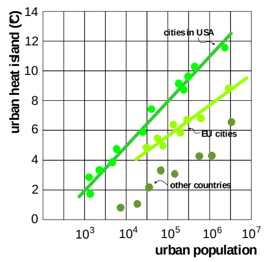
- Expected climate changes will effect the energy use in buildings.

  The figure shows expected number of hours with indoor temperature above 25°C in case of current conditions, different climate scenarios and in the year 2003.



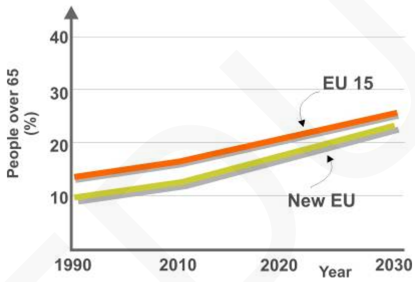
- Heat island in urban environment increase; summer time outdoor temperature in urban environment increase because rapid urbanization.

  Studies shows that even in small cities anal useful energy for cooling increase up to 10 kWh per m² of building area.



mporatnce of buildings cooling will increase in the future

- Buildings architectural characteristics and trends, like an increasing ratio of transparent to opaque surfaces in the building envelope (up to the popular all glass buildings) results in larger solar gains
- Increased living standard and new appliances increase internal heating gains in buildings.
- Ensuring good indoor climate is by far more important that energy demand itself; population in EU get older and older and more vulnerable to heat stress



Therefore cold is one of the important energy carriers in buildings.

Energy demand for cooling of the buildings

- Mechanical cooling, normally used nowadays, increase the use of electricity, high-exergy form of energy which is produced with highest emissions of green gases.
- In Germany the overall electricity demand for building air conditioning in 2006 was approx. 5% of the total electricity consumption. In other south European countries this share might be far higher.
- Cooling systems have high simultaneousness peak load factor. In Slovenia peak load in electricity supply grid changes from 19 o'clock in winter months in mid 80' to 15 o'clock in summer days, supposed because increased number of cooling devices.
- The sales rate in 2008 for small size electrically driven room air conditioners (< 5 kW chilling capacity) was approx. 82 million units worldwide, of which 8.6 million were sold in Europe. In Slovenia, country where cooling of the buildings is not common, it is expected that number of flats with mechanical cooling will increase from ~ 15% to 35% till 2020.

Case study

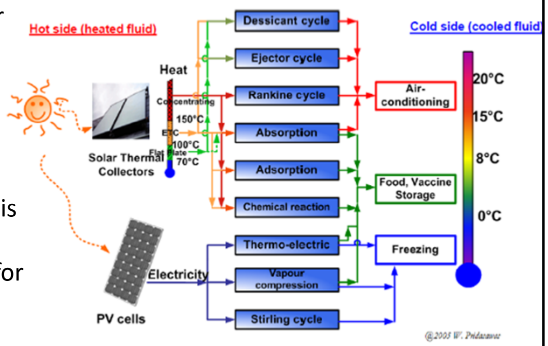
Cooling load and energy demand in four office/public buildings.

		Cooling load (W/m³)	Cooling load (W/m²)	Useful energy demand (heat) (kWh/m²)	End energy demand (electricity) (kWh/m²)
Office building 1		7.7	21	8	3.4
Office building 2		31	84	51	18.7
Office building 3		14	38	29	10.6
Shopping centre		21.6	76	58	19.2

Solar assisted cooling

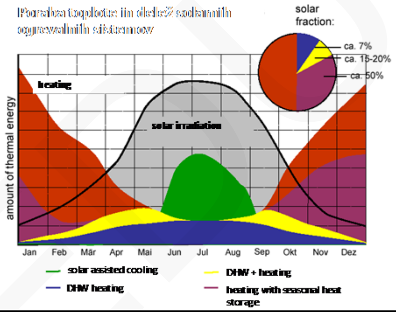
- Beside rational energy use measures, one of the most promising techniques for improving summer time indoor living comfort, meanwhile decreasing energy demand in buildings, is so-called solar assisted cooling.

  There are two basic technologies enable for solar cooling:
  - PV systems, witch converts solar energy directly to electricity (see Lecture #11) and can be used for thermoelectric, Stirling cycle or compressor driven mechanical cooling;
  - thermal solar systems that are upgraded with systems that use/converts heat into cold. This chapter will focused on such technologies and applications for cooling/air-conditioning of the buildings.



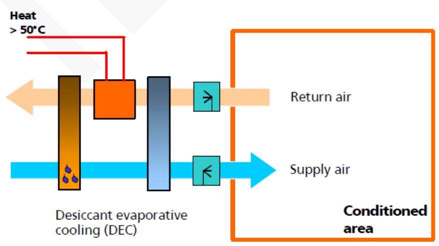
Solar assisted cooling

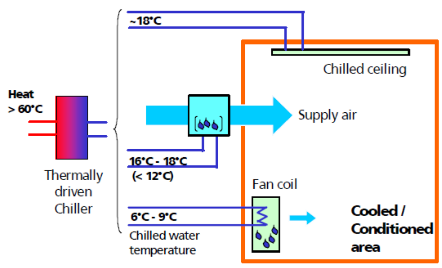
- Solar assisted cooling improves sustainability of the building because:
  - enable considerable savings in primary energy consumption and reduction of CO_2 emissions;
  - enable the “peak shaving” in public electricity grid;
  - enable combined use of solar heating, cooling and domestic hot water preparation which improves all year efficiency of thermal solar systems and increase economy of solar systems;
  - lower noise emission.



Solar assisted cooling – general principles

- “Open cycle” solar assisted cooling - supply air is directly cooled and dehumidified in air handling unit (AHU).
- “Close cycle” solar assisted cooling – chilled water (5°-10°C) produced and transferred to the decentralized units like fan-coils, chilled ceilings or AHU

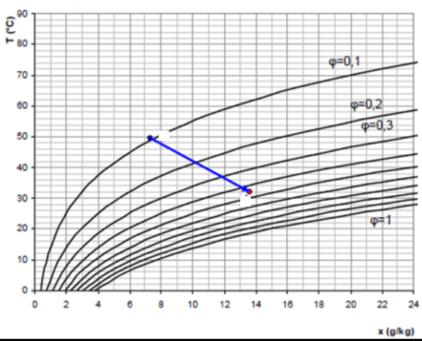


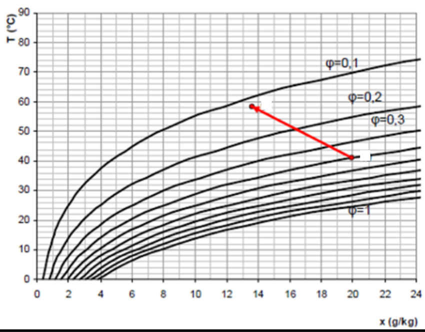


- Bought technologies need for operation the heat from thermal solar system, but they differ regarding to the temperature level of the solar heat – 50 to 60°C in case of open cycle and 80 to 95°C (+) in case of close cycle.

- Open cycle solar assisted cooling is so called desiccant-evaporative cooling (DEC) because of thermodynamic processed that are used for changing of air thermodynamic state.
- Beside air heating or cooling when temperature is changed by absolute humidity remain constant, two other processes, related to latent heat transfer, are needed for desiccant-evaporative cooling:
    - humidification and
    - dehumidification of the air.

- During the humidification, water droplets transforms into molecules of water vapour. Consequently the air cools down, but moisture increase and this can cause uncomfort conditions in buildings. This kind of natural cooling could be very effective if humidity of the air is low.
- In reversible process, called sorption, dehumiditification of the air is going on and results in lower absolute air humidity, meanwhile the temperature of the air rise. Sorption mater can be solid (eg. silicagel) or liquid (LiBr). Water vapour molecules must be discharged from sorption mater by the additional heat.

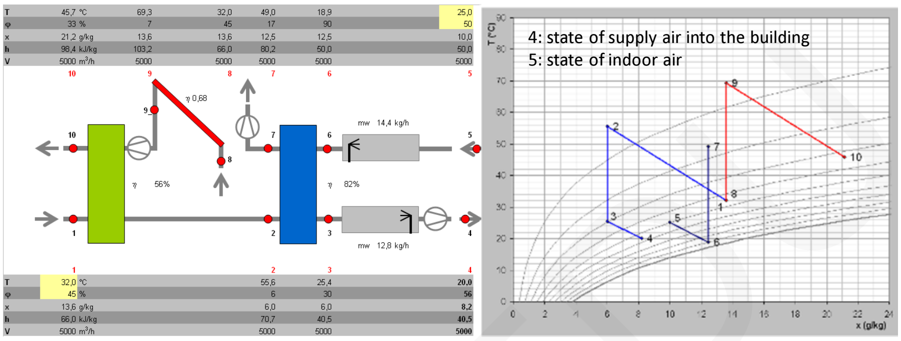




Solar assisted cooling – thermodynamics behind the story

- Here is complete process of DEC (in one of the possible configurations)

5-6: cooling of rejected indoor air with humidifier
6-7: cooling of supply air with rejected indoor air
8-9: heating of outdoor air with solar collectors
9-10: dehumiditification of sorption exchanger with hot air from solar collectos



1-2: dehumiditification of the supply (fresh) air in sorption exchanger
2-3: cooling of supply air with rejected indoor air in counter flow heat exchanger
3-4: cooling of supply air with humidifier

Solar assisted cooling – thermodynamics behind the story

- Close cycle solar assisted cooling is so sorption cooling. Sorption actually refers to the action of absorption or adsorption. In principle both technologies are used in refrigeration, whereas absorption cooling is more common.

- The absorption cycle is a process by which the refrigeration effect is produced through the use of two fluids (called refrigerant and absorbent) and some quantity of heat input.

- The most widely used refrigerant and absorbent combinations in absorption refrigeration systems are ammonia-water and lithium bromide-water pairs.

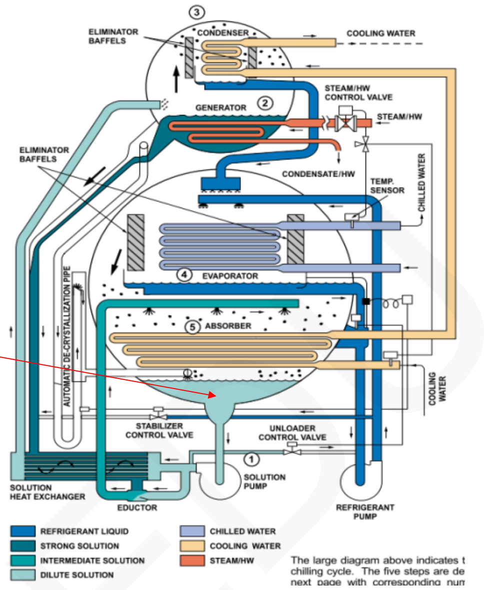
- The lithium bromide-water pair is available for air-conditioning and chilling applications (over 4°C, due to the crystallization of water). Ammonia-water is used for cooling and low temperature freezing applications (below 0°C).

Source: York

- Scheme presents (obvious not simple) absorption cooling system. In “generator” heat must be supplied and it can be provide by solar collectors.

(York)

- A dilute lithium bromide solution is collected in the bottom of the absorber shell. From here, hermetic solution pump moves the solution through a shell and tube heat exchanger for preheating.

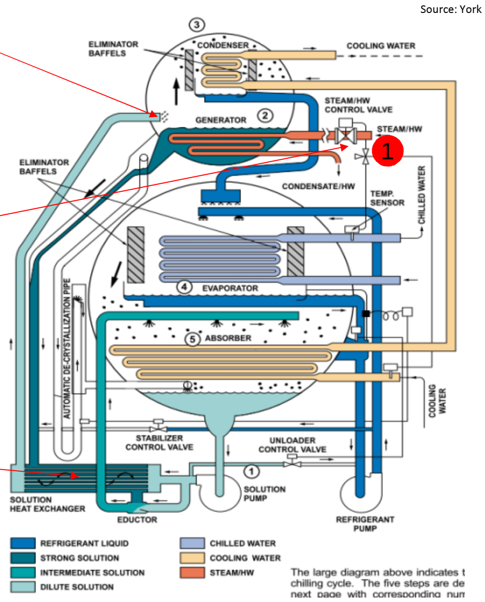


Solar assisted cooling – thermodynamics behind the story

Source: York

- After exiting the heat exchanger, the dilute solution moves into the upper shell. The solution surrounds a bundle of tubes which carries either steam or hot water.

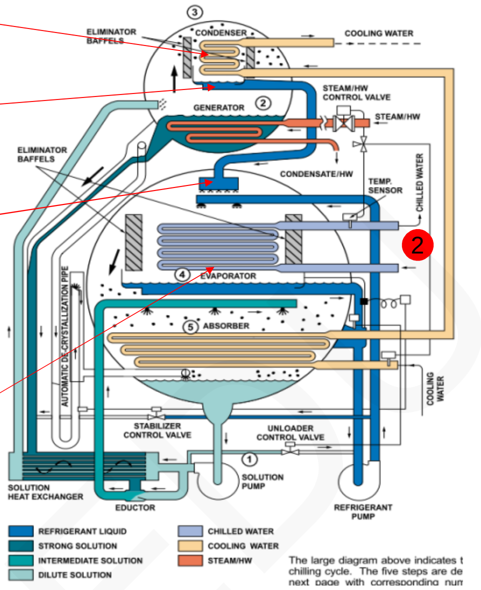
- Hot water from solar collectors transfers heat into the pool of dilute lithium bromide solution. The solution boils, sending refrigerant (water) vapor upward into the condenser and leaving behind concentrated lithium bromide. The concentrated lithium bromide solution moves down to the heat exchanger, where it is cooled by the weak solution being pumped up to the generator.



Solar assisted cooling – thermodynamics behind the story

- The refrigerant vapour condenses on the condenser tube bundle. The heat is removed by the cooling water. Condensed refrigerant is collects at the bottom of the condenser.
- Liquid refrigerant flows from the condenser in the upper shell down to the evaporator in the lower shell and is sprayed over the evaporator tube bundle.
- Due to extreme vacuum in the lower shell (0.8 kPa of absolute pressure), the refrigerant liquid boils at ~ 4°C, creating the refrigerant effect. The vacuum is created by hygroscopic process - the strong affinity lithium bromide for water.

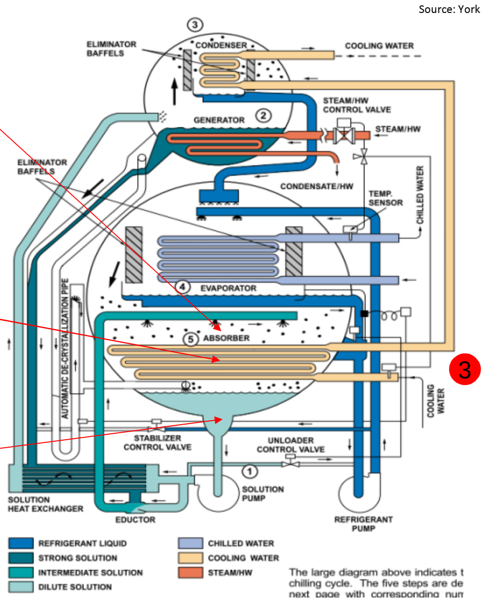
Source: York



Solar assisted cooling – thermodynamics behind the story

- As the refrigerant vapor migrates to the absorber from the evaporator, the strong lithium bromide solution from the generator is sprayed over the top of the absorber tube bundle. The strong lithium bromide solution actually pulls the refrigerant vapor into the solution, creating the extreme vacuum in the evaporator.
- The absorption of the refrigerant vapor into the lithium bromide solution also generates heat, which is removed by the cooling water.
- Dilute solution of lithium bromide is collect at the bottom of the lower shell, where it flows down to the solution pump. The chilling cycle is now completed and the process begins once again.

Source: York



Solar assisted cooling – thermodynamics behind the story

Source: York

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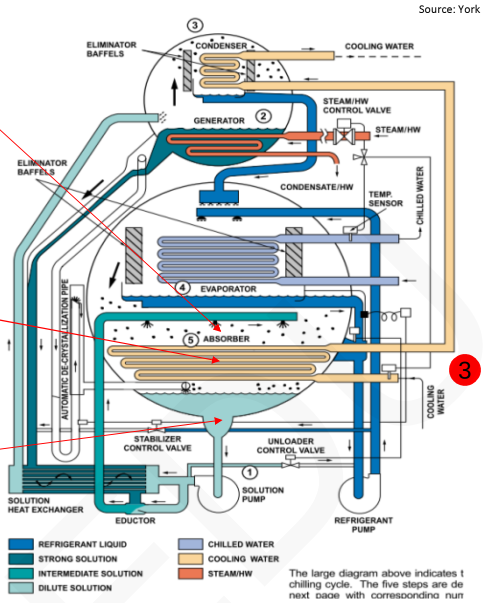
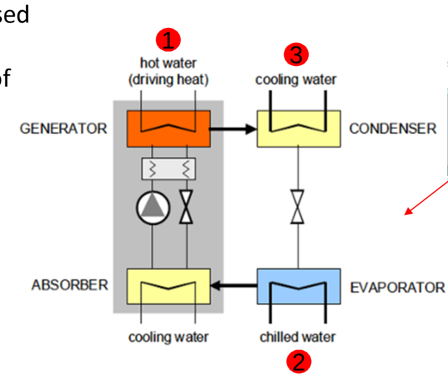
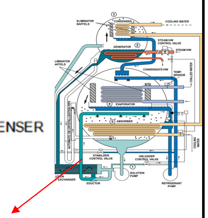


Solar assisted cooling – thermodynamics behind the story

Source: York

- Instead of described one step absorption cycle, two stage, more efficient, absorption cooling can be used
- Quite complicated scheme of sorption chillier can be simplified like this:



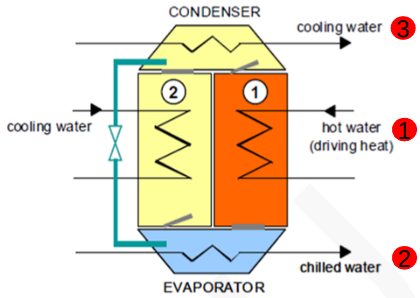


Absorption chillers with cooling power between 5 kW to 10 MW are market available. Here two units with cooling power 5 and 15 kW are shown

Solar assisted cooling – thermodynamics behind the story

- Instead of liquid absorbent, solid one can be used in case of adsorption cooling. In this case sorption material adsorbs the refrigerant, while it releases the refrigerant under heat input. A quasi-continuous operation requires for at least two compartments with sorption material allowing regeneration of adsorption material. In most cases water as refrigerant and silica gel or zeolithes as sorbent are used.

- Comparing to absorption chillers, adsorption runs with lower driving temperatures (65°C to 75°C), but produce chilled water with higher temperatures



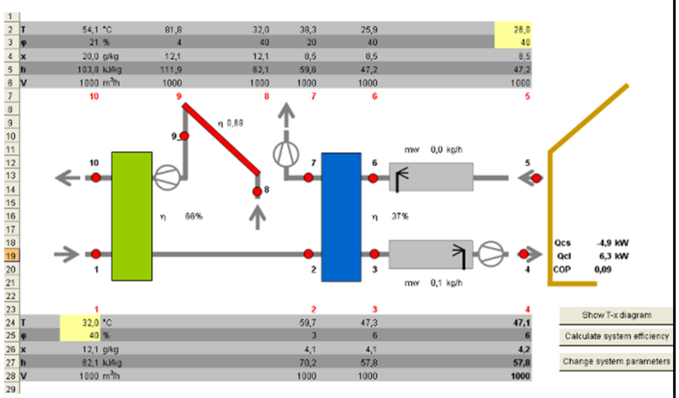
Two small adsorption chillers with cooling power 7,5 and 70 kW

Solar assisted cooling – efficiency

- Efficiency of solar assisted cooling systems are expressed by “coefficient of performance” COP. This is the ratio between the amount of produced cold (correctly removed heat) and sum of the needed heat in the same time period

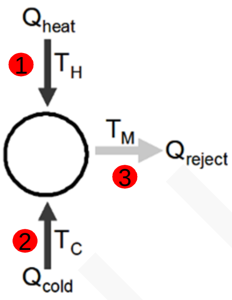
COP = Qc / Qh,solar

- The efficiency of DEC solar assisted cooling depends strongly on current state of the outdoor and indoor air and solar collectors efficiency. It must be calculated on the hour-to-hour based.



Solar assisted cooling – efficiency

- Theoretical COP of solar assisted absorption cooling is defined by all three relevant temperatures:
  - 1 T_H temperature of heat source (driving heat),
  - 3 T_M temperature of cooling water (ambient)
  - 2 T_C temperature of chilled water



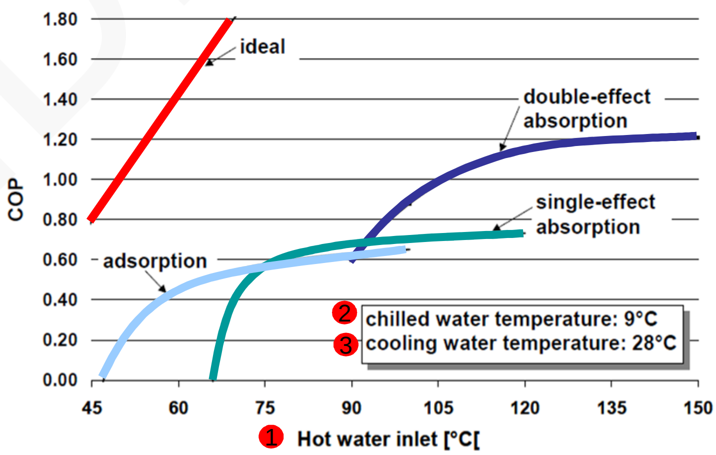
$$COP_{ideal} = \frac{T_C}{T_H} \cdot \frac{(T_H - T_M)}{(T_M - T_C)}$$

- Important: When product is presented, all three operating conditions must be stated ! (Source: Rotartica)

Factor de capacidad para instalaciones				
	Tipo de Instalación			
Tsuministro a Generador (de panel solar + caldera apoyo)	Factor de Capacidad Norma ARI 560; 2000	**Int**: fancoil (7-12º C) **Ext**: Torre refrigeración (29º C)	2 **Int**: suelo/techo radiante (18-20º C) **Ext**: disipación seca (38-42º C)	2 **Int**: fancoil (7-12º C) **Ext**: disipación seca (38-42º C) 3
80º C	0,8	5,6 kW	4,2 kW	2,5 kW
90º C	0,9	6,3 kW	5,5 kW	3,5 kW
1 **100º C**	1	7,0 kW	6,8 kW	4,5 kW
110º C	1,15	8,1 kW	7,8 kW	5,5 kW
120º C	1,4	9,8 kW	9,5 kW	6,7 kW

Solar assisted cooling – efficiency

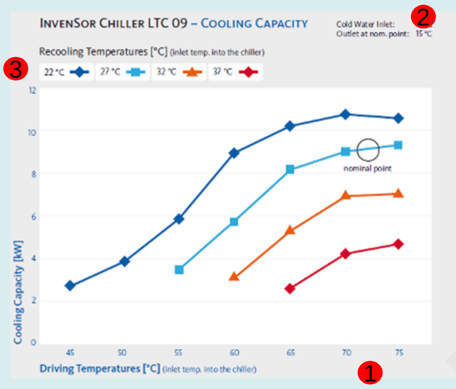
- The COP of solar assisted cooling systems is lower them COP_{ideal}.

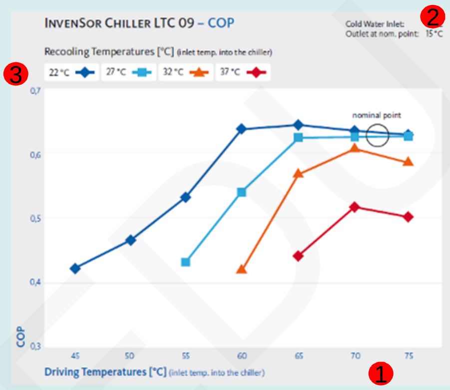


Case study

- Cooling power and COP of InvenSol LTC 09 adsorption chiller as a function T_H, T_M and T_C !

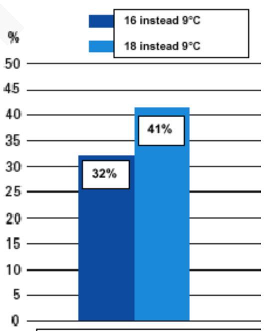
1 3 2





Solar assisted cooling – efficiency

- The COP of solar assisted cooling can be increased if higher temperature of chilled water is needed; for example if building constructions are thermally activated with chilled water



Decrease in energy consumption for cooling with higher temperature of chilled water

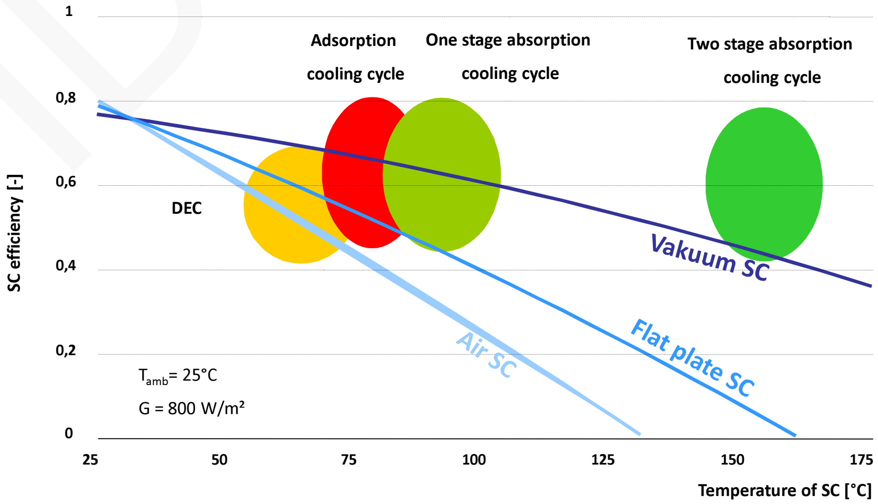
- The COP of solar assisted cooling can be increased if temperature of cooling water is lower; dry, wet or ground heat exchangers can be used for reject heat from sorption process to environment (at T_M).
- In hot climate wet cooling towers are needed causing significant increase in electricity consumption.
- Ground boreholes enable heat sink at constant and low temperature enable high COP. The investment is high since 50 m long borehole transfer only ~ 1kW of heat flux.

Solar assisted cooling – overview of solar assisted cooling technologies

Technology	Closed-cycle absorption (single-effect)	Closed-cycle absorption	Closed-cycle adsorption	Open-cycle solid desiccant	Open-cycle liquid desiccant
Refrigerant	H_2O	NH_3	H_2O	-	-
Absorbent	LiBr	H_2O	Silica gel	Silica gel	CaCl, LiCl
Chilling carrier	Water	Water-glycol	Water	Air	Air
Chilling temperature	6 - 20°C	-60°C to 20°C	6-20°C	16 - 20°C	16 - 20°C
Driving temperature	80 - 110°C	100 - 140°C	55 - 100°C	55 - 100°C	55 - 100°C
Cooling water temperature	Up to 50°C	Up to 50°C	Up to 35°C	Not applicable	As low as possible
Cooling power range	35 - 7000 kW	10 - 10000 kW	50 - 430 kW	20 - 350 kW	
COP	0,6 - 0,75	0,6 - 0,7	0,3 - 0,7		

Solar assisted cooling – selecting solar collectors

- Different solar assistant cooling systems required different driving temperatures. This affect SC efficiency and have influence on selecting the type of SC (with sufficient high efficiency)



Solar assisted cooling – selecting solar collectors

- In case of more efficient two-stage absorption cooling cycle, temperature heat source should be 150°C or more. Even vacuum solar collector could be inefficient in this case, if solar radiation decrease. Concentrated solar collectors (CSC) could be used instead.

Source: Broad Technology Centre, China; CSC for driving two stage absorption chiller. In flasher steam is generated from hot water (180°C). Chillers cooling power in range of 16 kW (CSC 32m^2) up to 580 kW (CSC 1024 m^2)

CSC in Dalama, Turky. Ciller cooling power 116 kW, CSC 180 m^2.

Solar assisted cooling – sizing of solar collectors

- Role of thumb

If thermal solar system is dominant source of heat the approximate size can be estimated:

cooling load (kW)

area of solar collectors (m^2)

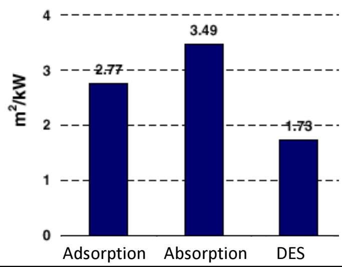
$$A_{SC} = \frac{Q_c}{G_{SC} \cdot \eta_{SC} \cdot COP} \rightarrow 3{,}7\ m^2/kW$$

nominal solar radiation (0,8 kW/m^2)

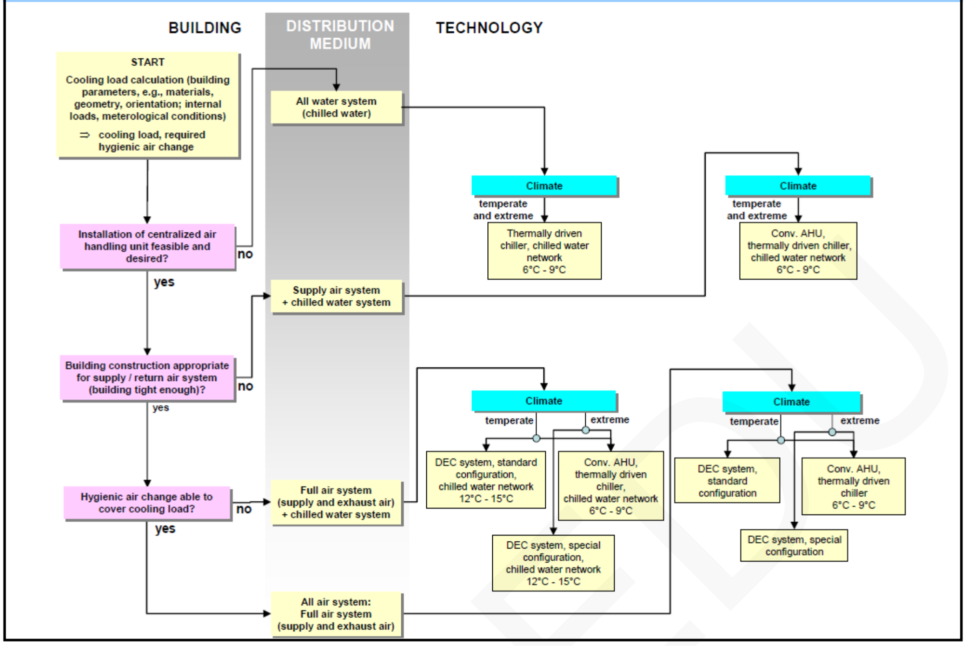
solar collectors efficiency (~0,5)

design COP ~ 0,75

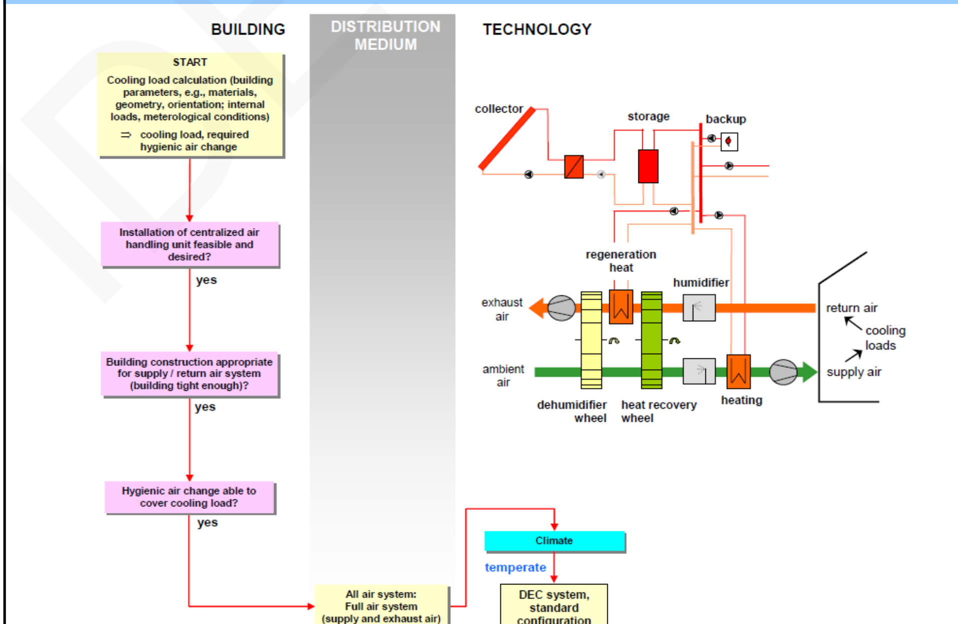
Taken into account selected design values 3,7 m^2 of SC is needed for 1 kW of cooling load ! On figure: specific SC areas in operating solar cooling systems in EU



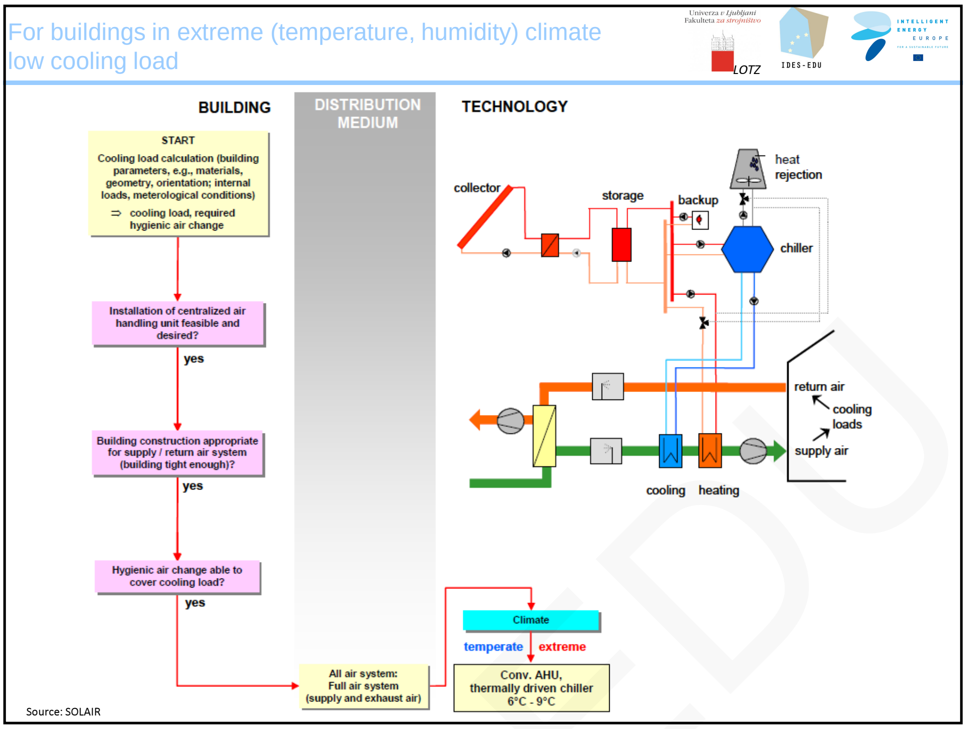
Selection of the appropriate technology – selection tree



For buildings in temperate climate having low cooling load



Source: SOLAIR


For buildings in extreme (temperature, humidity) climate
low cooling load
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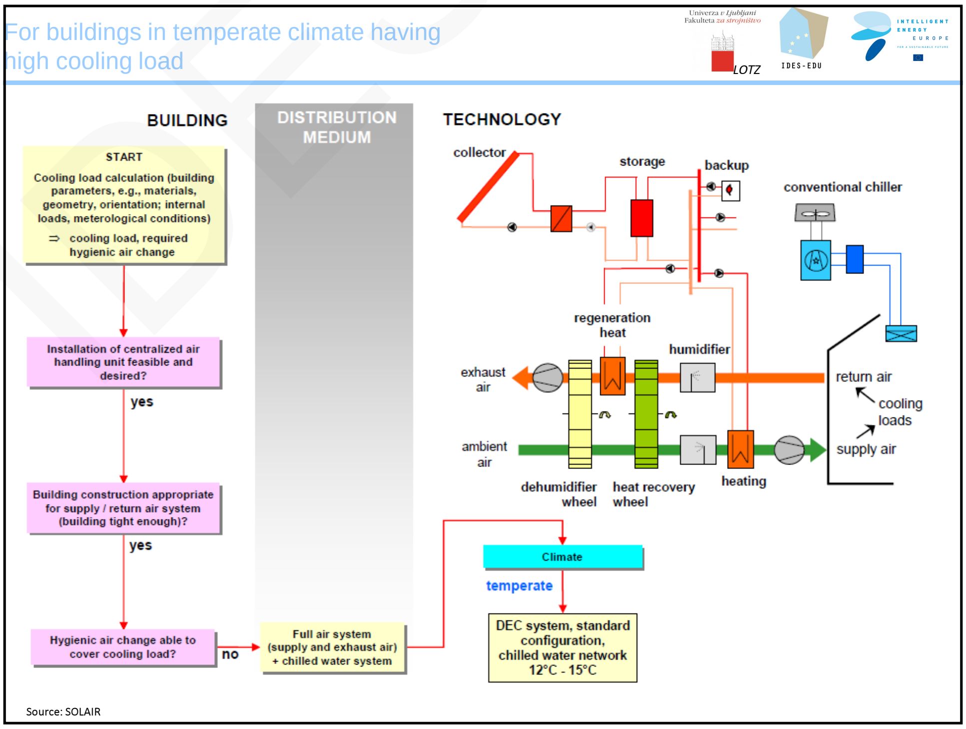
BUILDING
DISTRIBUTION MEDIUM
TECHNOLOGY
START
Cooling load calculation (building parameters, e.g., materials, geometry, orientation; internal loads, meterological conditions)
⇒ cooling load, required hygienic air change
Installation of centralized air handling unit feasible and desired?
yes
Building construction appropriate for supply / return air system (building tight enough)?
yes
Hygienic air change able to cover cooling load?
yes
All air system: Full air system (supply and exhaust air)
collector
storage
backup
heat rejection
chiller
return air
cooling loads
supply air
cooling
heating
Climate
temperate
extreme
Conv. AHU, thermally driven chiller 6°C - 9°C
Source: SOLAIR


For buildings in temperate climate having
high cooling load
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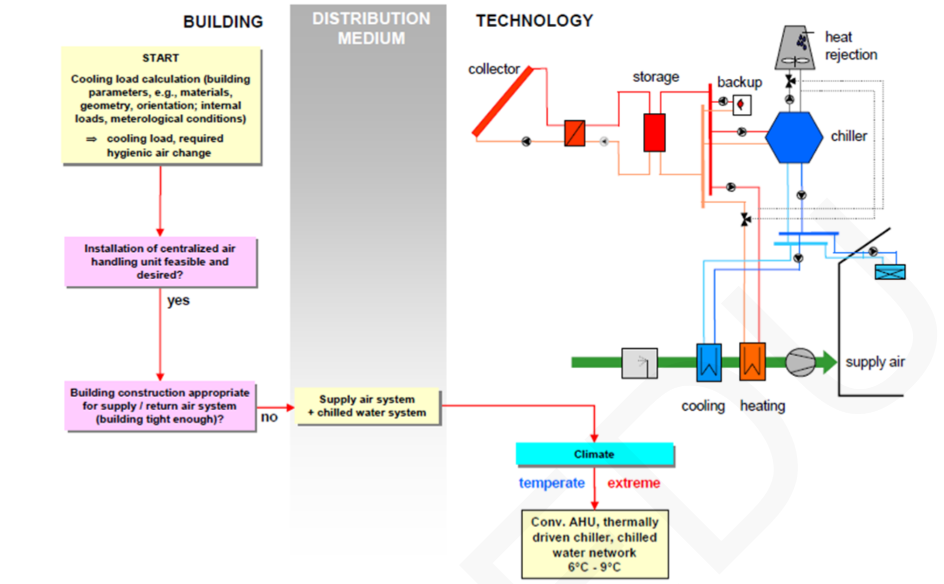
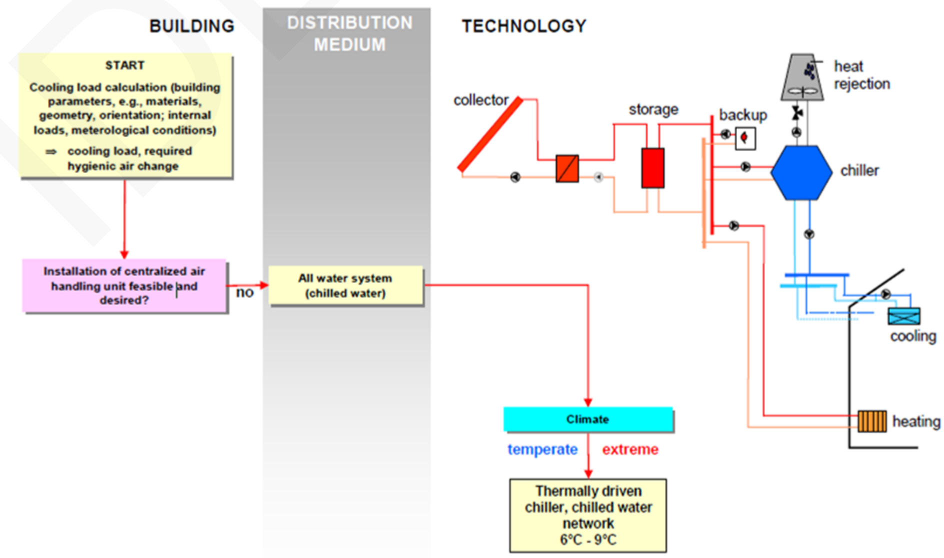
START
Cooling load calculation (building parameters, e.g., materials, geometry, orientation; internal loads, meterological conditions)
⇒ cooling load, required hygienic air change
Installation of centralized air handling unit feasible and desired?
yes
Building construction appropriate for supply / return air system (building tight enough)?
yes
Hygienic air change able to cover cooling load?
no
Full air system (supply and exhaust air) + chilled water system
collector
storage
backup
conventional chiller
regeneration heat
humidifier
exhaust air
ambient air
return air
cooling loads
supply air
dehumidifier wheel
heat recovery wheel
heating
Climate
temperate
DEC system, standard configuration, chilled water network 12°C - 15°C
Source: SOLAIR

For buildings in extreme (temperature, humidity) climate high cooling load



Source: SOLAIR

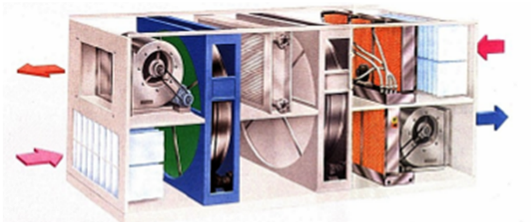
For buildings in extreme (temperature, humidity) climate high cooling load, close loop system only

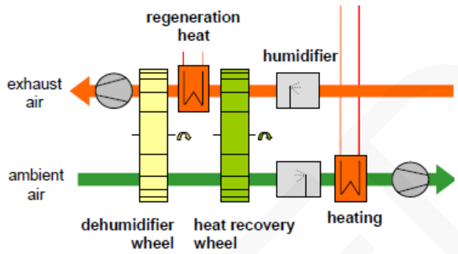


Source: SOLAIR

Solar assisted cooling – market available products

- Most of HVAC suppliers offer solar assisted DEC as well as part of AHU





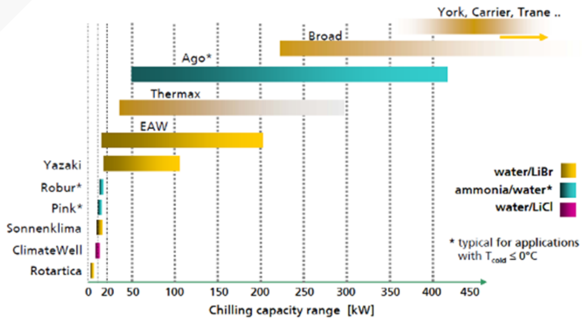
Source: SOLAIR

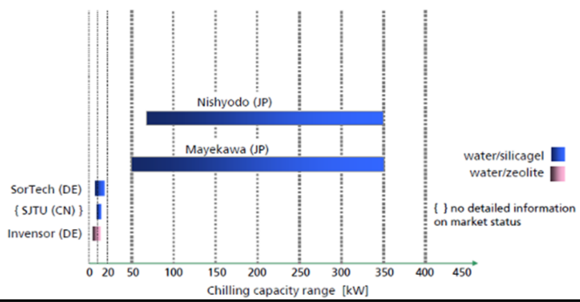
Solar assisted cooling – market available products

- There are several producers of sorption cooling units, absorption techniques is more developed then adsorption.

  Down sizing is main goal for producers.

- Adsorption chillers market is less developed, especially for small devices for the cooling of the buildings.

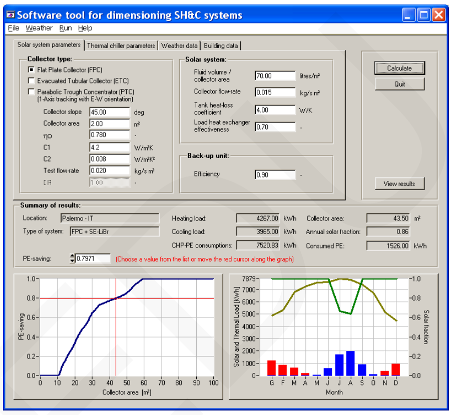




Source: SOLAIR

- Computer tools
- **SHC-Softwaretool (NEGST Project)**
  http://www.swt-technologie.de/html/publicdeliverables3.html.

The software tools allows for the determination of solar collector area required to achieve a given overall primary energy saving with respect to the most common conventional cooling system. The program considers both cooling and heating loads on monthly bases. The user needs to input the energy load per square meter of room area to be conditioned and the area of the room.

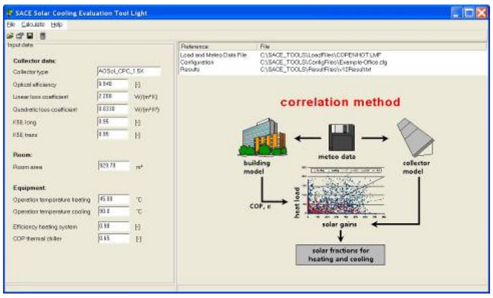


Source: SOLAIR

Sizing of the solar assisted cooling systems

- Computer tools
- “SACE: Solar air conditioning in Europe”.
  http://www.solair-project.eu/218.0.html

The objective of this software is to allow a quick pre-feasibility study of solar assisted air conditioning systems. The annual solar fraction for heating and cooling is calculated based on an hour-by-hour comparison of needed heat for a thermal driven cooling machine and available solar heat.



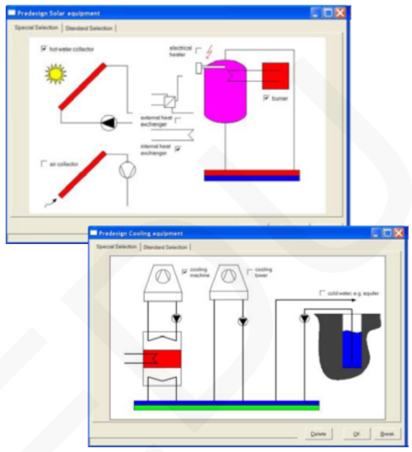
Source: SOLAIR

- Computer tools
- “**SolAC – Solar Assisted Air Conditioning Software**
  http://www.iea-shc-task25.org/english/hps6/index.html

The input data for the programme is weather data including solar radiation (hourly data), load files including heating and cooling loads (hourly data)

Four different units are considered in this software like solar system, cooling device, air handling unit, cooling and heating components in the room

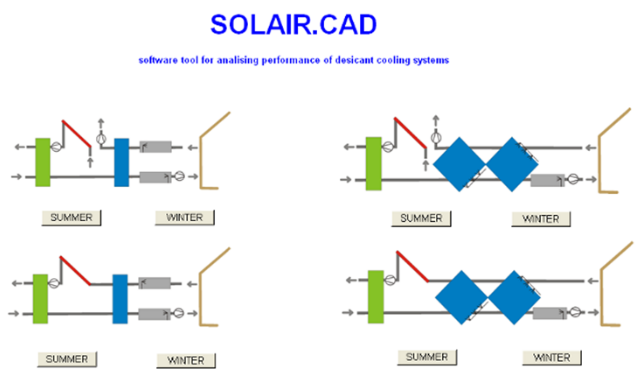
These units can have different configurations chosen by the user.



Sizing of the solar assisted cooling systems

- Computer tools
- “**SOLAIR.CAD**
  http://www.ee.fs.uni-lj.si

Tool for hour-by-hour evaluation of different configuration of open cycle DEC systems. Cooling as well as heating can be analyzed.

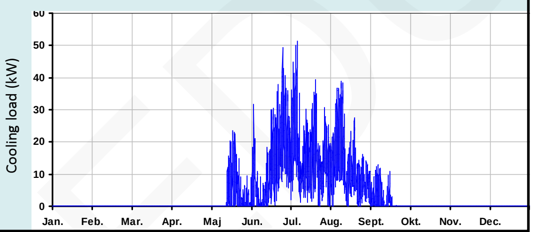


Source: SOLAIR

Case study

Feasibility study for Hospital Kranj (Slovenia)

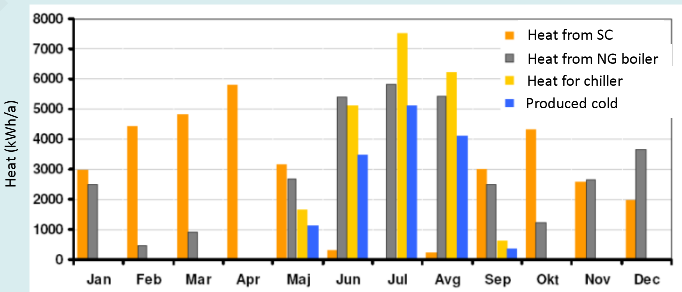
- Thermal response of the buildings was determinate using TRNSYS computer code.
- It was found out that indoor air temperature in typical hospital room is above 26°C more than 1100 hours per year.
- After energy renovation of building the cooling power is around 50 kW. Renovation includes installation of thermal solar system for DHW. This increase the economy of solar assisted cooling



Case study

- Solar assisted cooling system consist of vacuum solar collectors with aperture area of 80 m^2; heat storage with volume 6 m^3 and Yazaki absorption chiller. Hospital gain subsidies for 80% of total investment.

Nazivna hladilna moč	35,2 kW
Temperatura hladne vode	7°C / 12,5°C
Pretok hladne vode	1,52 l/s
Grelna toplota	50,2 kW
Temperatura grelne vode	88°C / 83°C
Pretok grelne vode	2,4 l/s (8,64 m^3/h)
Hladilno število - COP	0,7
Hladilna toplota	85,4 kW
Temperatura hladilne vode	35°C / 31°C
Pretok hladilne vode	5,1 l/s
Temperaturno območje grelne vode	70°C – 95°C
Območje hladilne moči	20 kW – 50 kW



Source : Yazaki

Case study

- Results:
  - Heat produced by solar thermal system – 33484 kWh/a
  - Share of solar heating for DHW – 50%
  - Driving heat for solar cooling – 21073 kWh/a
  - Produced cold – 14108 kWh/a
  - Share of solar cooling – 94%
  - Decreasing of natural gas consumption – 4000 m3/a
  - Decreasing of electricity use – 5000 kWh/a
  - Decreasing of CO_2 emissions – 11,4 t/a

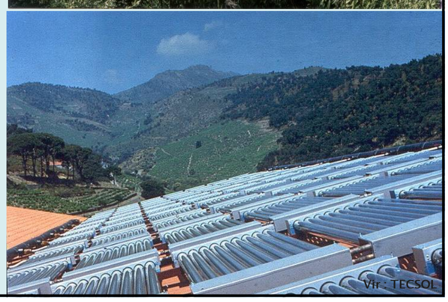
- Economics - simple return rate:
  - Investment 180.00 € /100.000 € if solar thermal system is excluded
  - Own investments: 27.000 € /15.000€ additional to solar thermal system
  - Simple return rate: 8 years / 5 years (even in case of high subsidies)

Case study

- Banyuls FR – wine cellar

  Site of the buildings - 4.500 m^2
  Instaled -1991
  Absorption solar cooling - Yazaki 52 kW
  Wet cooling tower
  Vakuum SC - 130 m^2
  Heat storage - 1 m^3
  Cold produced - 17.000 kWh/a
  Electricity use - 2.800 kWh/a

Source: SOLAIR



Vir.: TECSOL

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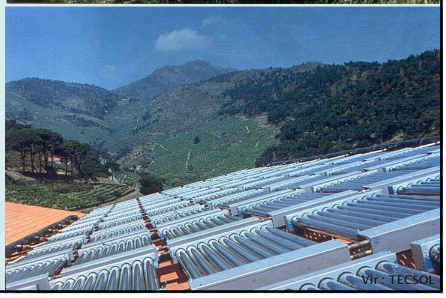


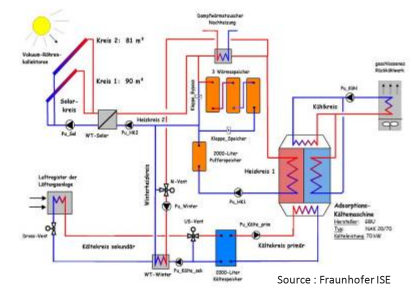
Source: SOLAIR

Vir : TECSOL

Case study

- Freiburg D – Hospital

Adsorption chiller Nishiyodo 70 kW
Wet cooling tower
Vakuum SC 170 m^2
Heat storage 6 m^3
Cold storage 2 m^3



Source: SOLAIR

Source : Fraunhofer ISE

Case study

- Hartberg A –office building

  Site of the buildings: 280 m2
  Instaled: 2000
  DEC 6.000 m^3/h; 30 kW
  Vakuum SC: 12 m^2
  Heat storage: 3 m^3
  Cold produced: 10.000 kWh/a
  Electricity use: 65 kWh/day
  Annual average COP: 0,6

Source: SOLAIR

Solar assisted cooling – environment issues

- Solar assistant cooling is environmental friendly because materials used as refrigerant and absorbent has no ozone depletion potential and no or little global warming potential.
- Solar assistant cooling compete with mechanical cooling nowadays with high COP (>3,5). Therefore planning the solar assisted cooling systems in a way to reduce energy consumption is crucial.

Solar assisted cooling –economic issues

- Solar assisted cooling can be nowadays justified if in this way obligatory share of renewable energy sources is assure or if adequate subsidies are granted.
- Solar absorption cooling systems cost are approximately up to 1.5 - 2 times more than a conventional (compressor driven) one.
- A fully equipped DEC air handling unit costs approximately up to 1.3 to 2 times more than a standard unit. This is about 5000 € per 1000 m^3/h of handled air or 1500 € for every kW of cooling power.
- Regarding to current researches and EPBD guidelines it can be expected that smaller and cheaper solar assisted cooling devices will be available in next years.

Self evaluation

- Describe why we expect that cooling of the buildings will increase energy demand in the future !
- Which techniques for cooling of the buildings can be implemented ?
- How differ so called “open” and “closed” solar cooling process ?
- What is the role of solar energy in solar cooling processes ?
- Describe absorption cooling cycle !
- Define COP of absorption cooling !
- Explain solar cooling !
- What you know about economics of solar cooling ?

L.D.D. Harvey; "A handbook on Low-Energy Buildings and District-Energy Systems, Earthscan, UK 2006

M. J. Moran, H. N. Shapiro: Fundamentals of Engineering Thermodinamics; John Wiley & Sons, USA, 1998

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www.solair-project.eu
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