Evaluation of solar concentrator configurations report

WP 1 - Deliverable 1

Solar collectors with static concentrator for solar thermal applications at intermediate and medium temperatures

Acronym: ScoSco

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1 Introduction to the research project ScoSco

In the SCoSCo project, **static concentrators** combined with suitable tracking absorbers are suggested in order to adapt efficient solar thermal collector operation in intermediate temperatures with effective extension to medium temperatures. Moreover, the solar thermal collector exhibits the flexibility for **building integration**.

1.1 Definition

According to the Task 49 of the Solar Heating and Cooling program (SHC) of the International Energy Agency (IEA), medium-temperature collectors are defined as those having a heat output of at least 300 W/m² (gross collector area) for 1 000 W/m² hemispherical irradiance with 15% diffuse fraction, 20 °C ambient temperature and an operating temperature of at least 100 °C [1]. Moreover, it is stated that the operating temperature of the collector should be up to 250 °C [2].
In literature several operating temperature ranges within which collectors are classified as medium temperature can be found. According to [3] the temperature range for medium-temperature solar collectors is between 80 to 250 °C. According to the STAGE-STE Project [4] medium-temperature collectors are defined in the range between 150 to 250 °C. According to [5] the operating temperature may vary between 100 and 300 °C. Nevertheless, in most cases a specific definition of the temperature level, applied area, hemispherical irradiance and diffuse fraction is not stated. Therefore, the definition of TASK 49 seems to be the most precise.

The various medium temperature collectors in the market are nowadays mainly based on the design concept of a parabolic trough collector (PTC), parabolic dish, compound parabolic collector (CPC), Fresnel type collector, high-vacuum flat plate collectors, fixed-mirror solar concentrator (FMSC), vacuum-tube collectors or combinations of these concepts [6].

Static concentrators are traditionally termed to Fixed Mirror Solar Collector (FMSC). Therefore the definition of a fixed mirror system seems to be more appropriate than the term static concentrator.

The reflectance properties of the reflector materials are provided in the Solar Paces Official Reflectance Guideline Version 2.5 [7].

2 Review

2.1 State of the art of medium-temperature collectors

Today many medium-temperature solar collectors are already on the market or under development. The PTC NEP PolyTrough 1800 was tested at the SPF in Switzerland, and an excerpt of the test report is published at the institute homepage [8].

Figure 1: Picture of the NEP PolyTrough 1800 [8] and a CPC concept [9].

Moreover a CPC type collector with a bifacial flat receiver was tested at the SPF [9]. The manufacturer and the performance data are not available. In the report the technology is considered as promising; a picture of the collector is shown in Figure 1 (right panel).

The Fresnel type state of the art collector LF-11 of Industrial Solar GmbH is already available on the market and turnkey plants using this type of collector are already built worldwide [10]. The specifications data sheet of the collector are available at the webpage of the manufacturer [11].

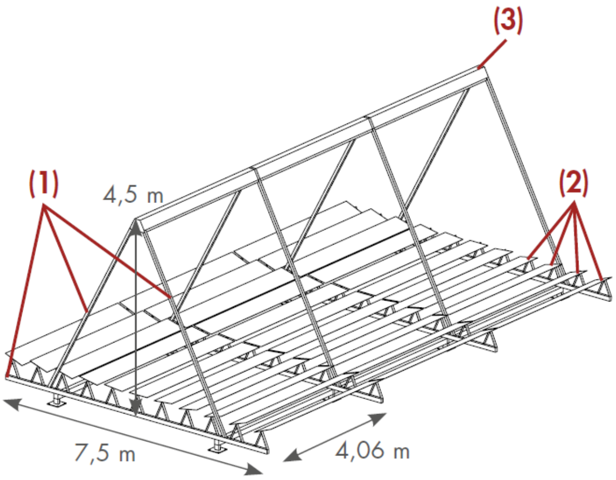


Figure 2: Schematic drawing of the collector LF-11 [11]with supporting structure (1), primary reflector (2) and secondary concentrator with receiver.

Another Fresnel type collector already available on the market is that of the Australian manufacturer Chromasun who has given to it the name Micro-concentrator. This is based on the concept of a large solar Fresnel field downscaled by the factor of approximately 100 to the size of a conventional onroof installation. The specifications of the single-axis tracking product MCT-HT-001 can be found at the company webpage [12]. The data provided in the company webpage are in some cases higher than those reported on the SCRR OG-100 certificate with the number 2010064A, which is linked on the same webpage; this certificate cannot be found at the homepage of the solar rating and certification corporation [http://www.solar-rating.org/certification/collector.html]. Since the SRCC certificate is an independent reference, those values are shown in the following table and diagram. The Chromasun webpage has not been updated since 2013.

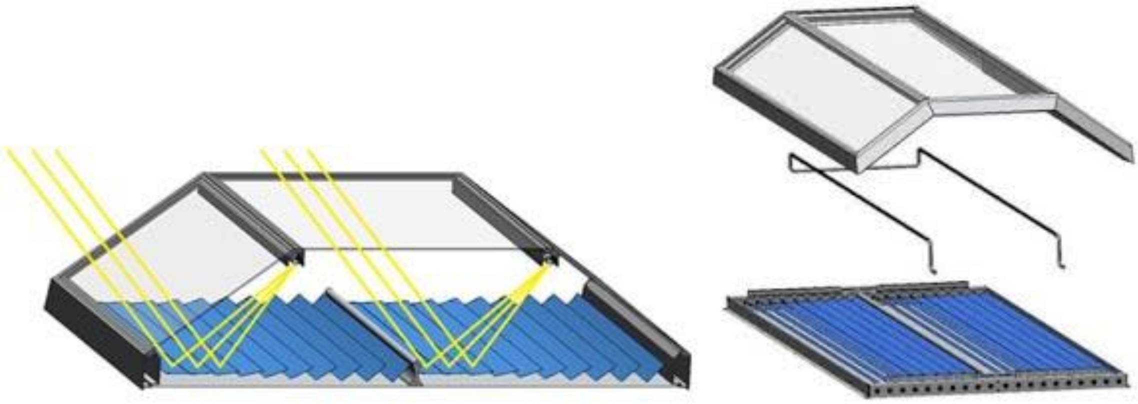


Figure 3: Schematic composition of the Fresnel type collector MCT by Chromasun.

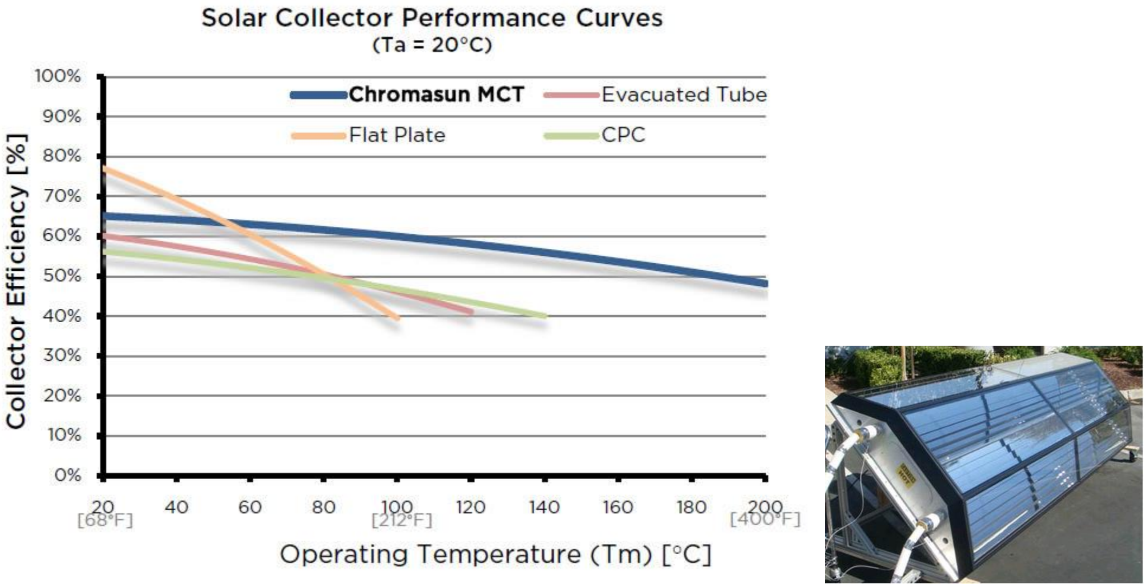
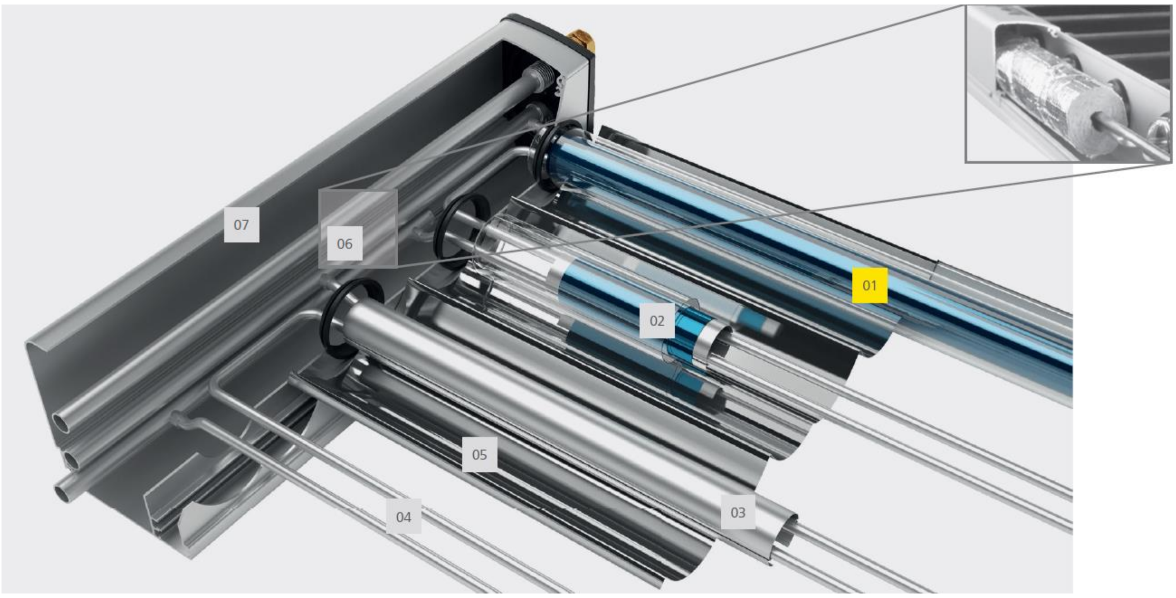


Figure 4: Performance curves and installation example of Chromasun MCT [12].

The data of the globally widespread CPC collector from Paradigma [13] can be obtained from the company webpage and also from a solar Keymark certificate. The collector is normally installed as a non-tracking collector.



1 Vacuum tube with Plasma-coating
2 selective coating at inner glas tube
3 aluminium heat transfer plate
4 U-shaped tube
5 CPC mirror
6 Insulation of mineral wool within the manifolder box
7 Cabinet

Figure 4: Cross section of the Aqua Plasma CPC collector [13].

The latest development in the field of medium temperature collectors at the SIJ resulted from the public funded projects PaRiS and PolyP [14], [15]. In the frame of PaRiS a reference collector was constructed and tested according to ISO 9806. The technical data are published in the final report of the project PaRiS at the Technische Informationsbibliothek (https://www.tib.eu).
In the frame of Poly-P a 2 m² aperture area collector for on-roof installation was developed and tested. Moreover, the concept of a polymeric twin-sheet body as construction support for an aluminium mirror was investigated [15].

More recently in 2018 at the Solarthermalworld.org webpage two new manufacturers of Fresnel type collector are mentioned. Solatom is a Spanish based manufacturer; they developed a complete pre-assembled collector for on-roof installation, in order to limit mounting and installation costs, as well as error during commissioning.

Figure 5: Solatom Fresnel-type collector [16].

Also the Austrian supplier Fresnex is offering a Fresnel type collector. The company delivers the solar thermal collector to a custom-built hybrid adsorption-compression chiller by the German-based company Fahrenheit. The aim of this combination is to demonstrate and promote a new benchmark cooling system for industrial applications [17].

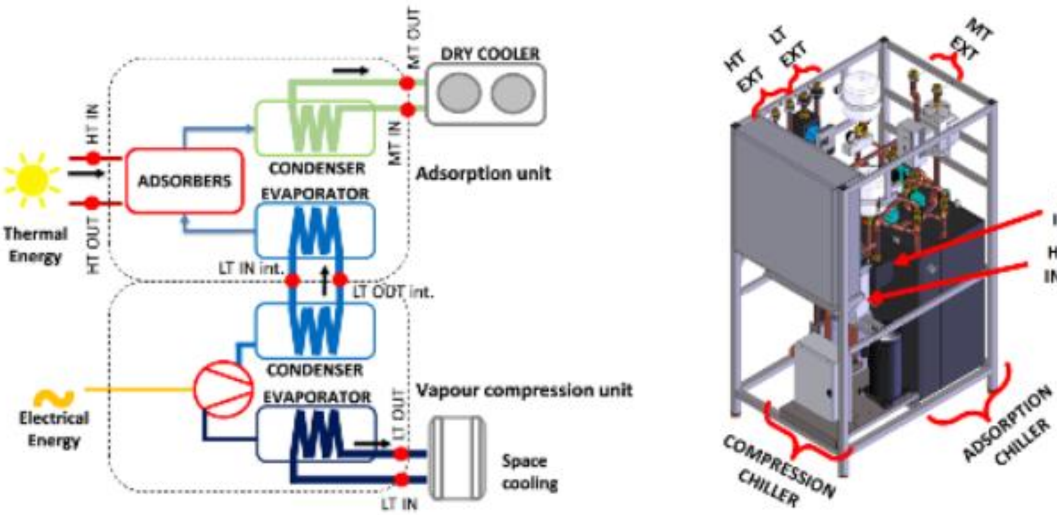


Figure 6: Hybrid adsorption-compression heat pump by the Fahrenheit company.

Figure 7: Fresnel-type collector by Fresnex [18].

Table 1: Overview basic performance data of medium temperature collectors.

Type and name	CPC Aqua Plasma	Fresnel type LF-11	PTC Paris_004, without vacuum	PTC Paris_004, with vacuum & Intercept	PTC NEP Poly Trough 1800	Fresnel type collector MCT
Manufacturer	Ritter Energie- und Umwelttechnik GmbH & CO.KG	Industrial Solar GmbH	Solar Institut Jülich SIJ	Solar Institut Jülich SIJ Potential	NEP Solar Pty Ltd	Chromasun
Optical efficiency η_0	0.687	0.663	0.710	0.782	0.689	0.565
Heat loss coefficient a_1 [W/m²/K]	0.613	0.0088*	1.19	0.36	0.36	0.54
Temp. Dependent heat loss coefficient a_2 [W/m²/K²]	0.003	0.00043	0.001541	0.0011	0.0011	0.0032
Concentration ratio c (Aperture area/Ab-sorber area)	~1 (calculated accord-ing to test report ITW 04 Col 338)	~34 (calculated according to data specification of the company and Schott PTR70 receiver, here: aperture area = mirror area)	9.4 (according to SIJ test re-port Coll_15_01)	9.4 (according to SIJ test re-port Coll_15_01)	17.1 (calculated with data according to SPF fact-sheet C1549)	11.3 (calculated with data according to SRCC certi-fication 2010064A)
comment	Solar Keymark cer-tificate, various dimensions, ISO 9806 tested	with 100% clean primary and secondary reflectors and receiver glass tube η_0=0.635 sun at zenith, Schott PTR70 Receiver * a_1 estimated by author as radiative losses: ~6W/(m²K)*ε/c with ε=5%, c=34, data with respect to mirror area	Report Coll_15_01 based on G_{use}, Data from final report	Potential collector Paris_004 with: Assumption: optimized receiver, Intercept 0.98 [-] and Reflectivity 0.90 [-]	Report from Homep-age SPF / Switzerland No.: C1549 gross width 1.965	Fresnel type collector with casing quasi dynamic testing

For the different collectors according to Table 1 the instantaneous collector efficiency versus the reduced temperature difference is provided at the following Figure. The reduced temperature difference is calculated as followed: $T^*m = \frac{(T_m - T_{amb})}{G_b}$ (Nomenclature according to ISO 9806:2013)

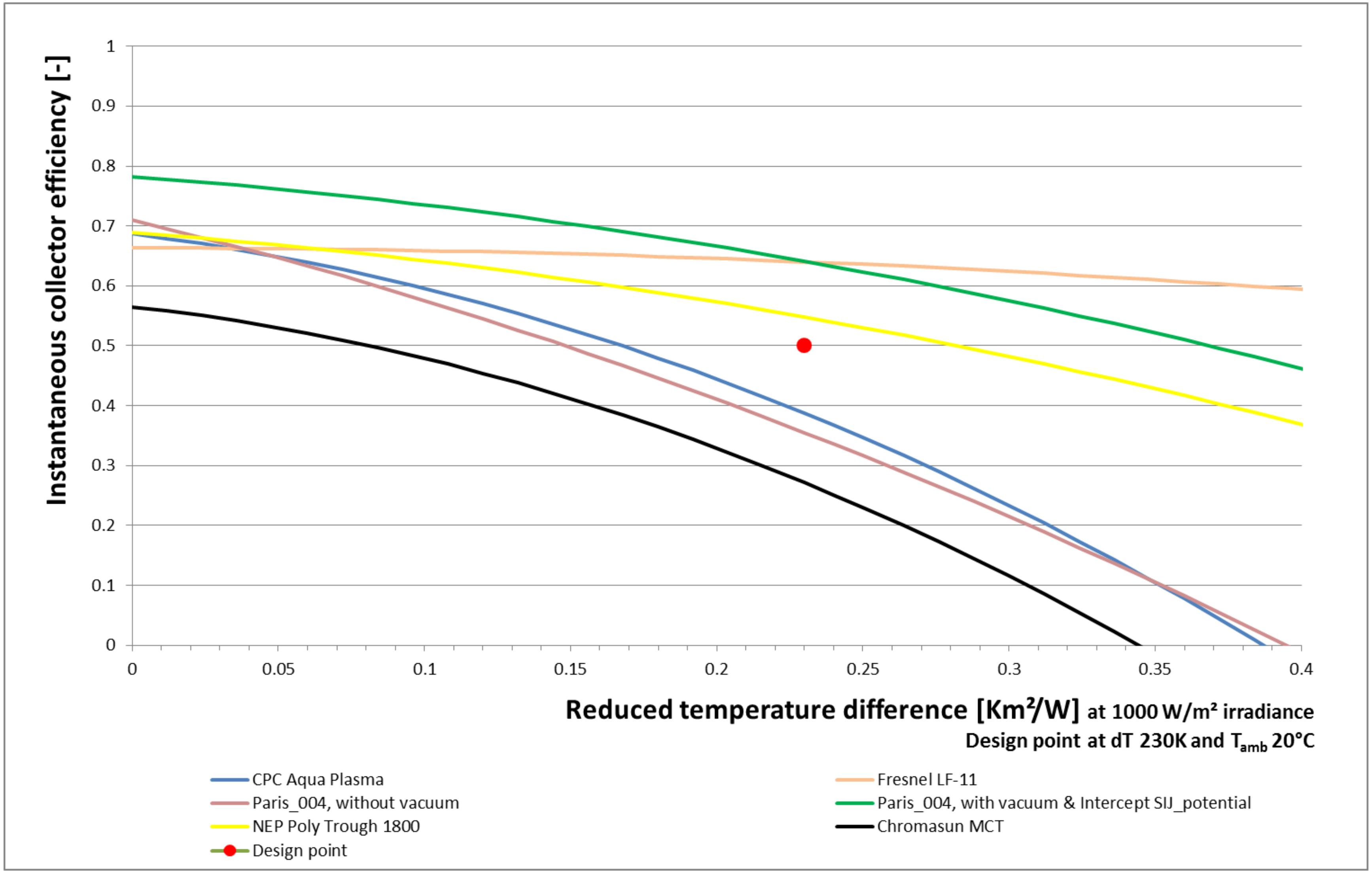


Figure 8: Comparison of different medium temperature collectors regarding the efficiency versus the reduced temperature difference.

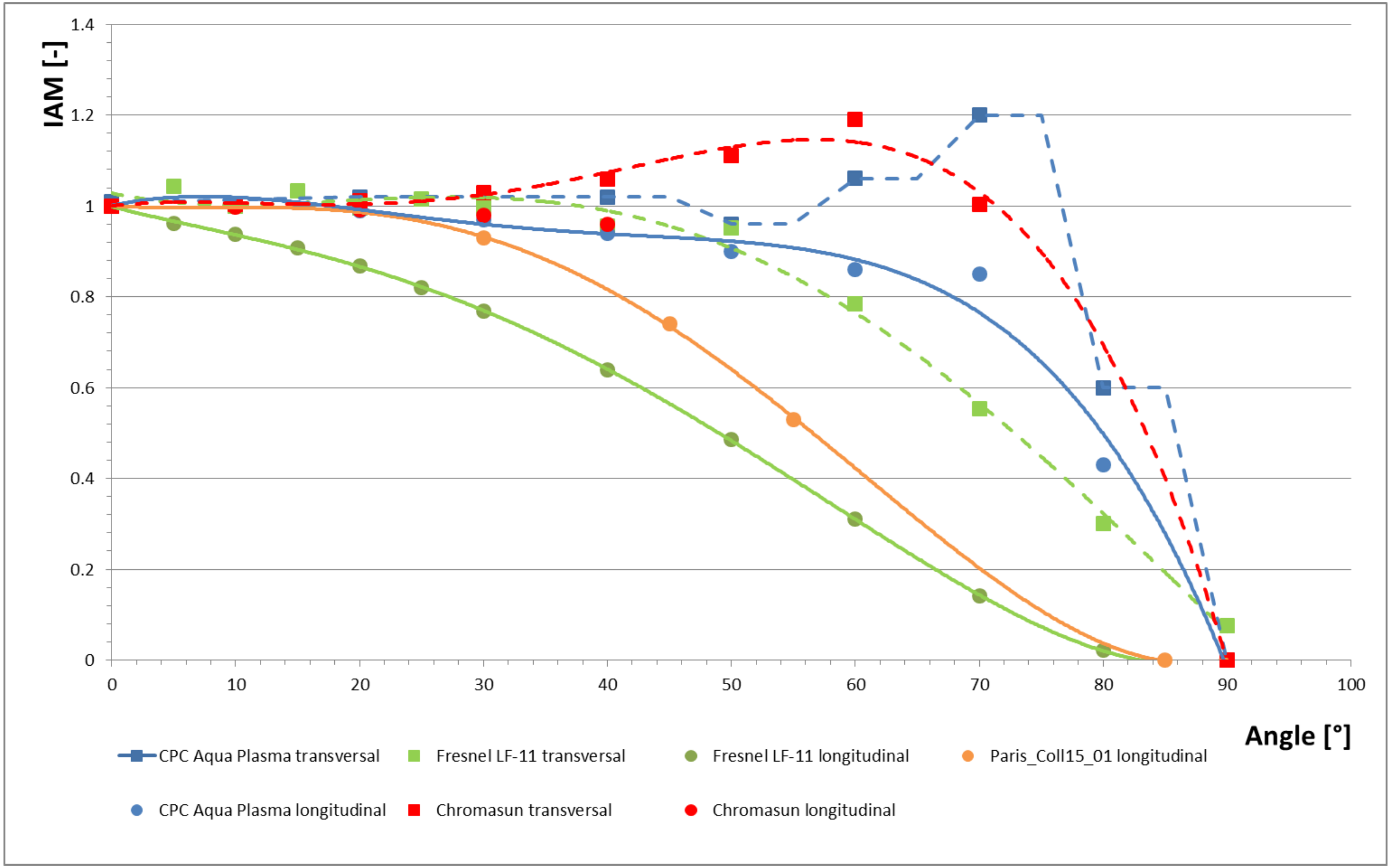


Figure 9: Comparison of different medium temperature collectors regarding the IAM (Incidence Angle Modifier), if available.

2.2 Fixed mirror for medium temperature collectors

2.2.1 2D systems (linear focus)

In the AEE journal 2006-02 by the Arbeitsgemeinschaft Erneuerbare Energie from Austria a prototype of a fixed mirror solar collector is shown [19]. The reflector is designed that the device can be directly integrated in the building envelope. In the article Moll and Schweiger argue that due to the graded shape of the mirror, a portion of the incident radiation falls on the steps, and not on the reflective surface and therefore the theoretically possible energy yield is reduced. A possible and logical modification of the design is therefore the transition to parabolically curved mirrors. It is well known that a parabola has an exact focus only when exposed vertically directly towards the sun. However, it can be shown that the broadening of the focus is limited at any angle of incidence. Compared to the design with a stepped mirror, the advantage of this design is that the mirror surface consists of a single continuous and smooth surface. However, according to the authors, the concentration factor to be achieved is limited to about C = 15.
For oblique incidence of the solar radiation, the FMSC has in principle a lower optical efficiency with respect to the mirror area, in comparison with a tracked parabolic through collector, because the cosine of the angle of incidence has to be taken into account. However, in relation to the existing base or roof area as a reference, the ratio reverses, as fixed mirror collectors can exploit almost 100% of the existing area, while the ratio of mirror area to ground or roof surface is limited to a maximum of 50% for parabolic troughs, to avoid mutual shading.
Moll and Schweiger predict a cost savings potential of about 25% in comparison to a flat plate collector and state a value of 220 €/m² for the turnkey installation of solar plant.

Figure 10: FMSC development with building integration [19].

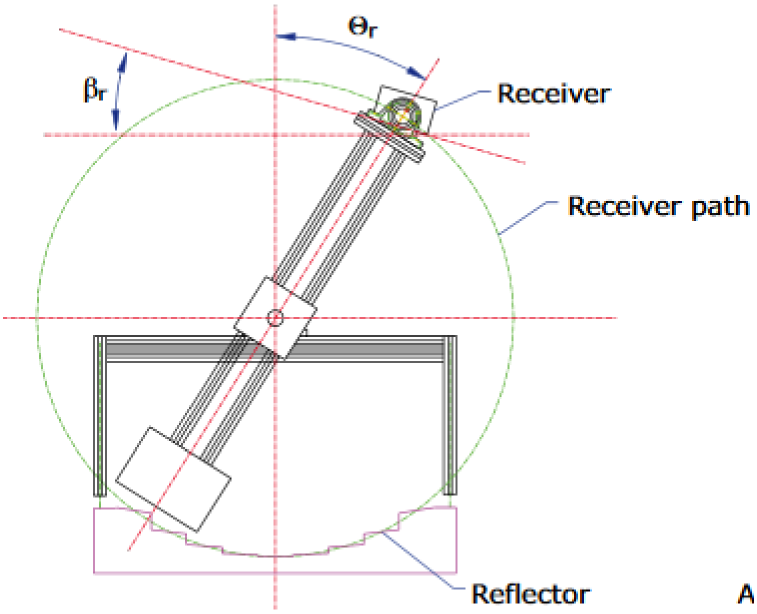


Figure 11: Cross section view [20].

Nadal and Moll [21] concluded that their FMSC concept can reach 200 °C with an annual efficiency up to 51%, depending on the location. This technology has been patented by the Spanish company Technologia Solar Concentradora SL. However, the weblink of the company, mentioned in [21], is not addressable anymore.

The Martinez and Pujol [22] developed the CCStaR collector and built a prototype. Based on the FMSC concept by Russell [23] they use one parabolic trough element as a reflector and conventional vacuum tubes (Sydney) as receivers. In order to reduce the cost of the tracking system, the receivers were arranged in arrays of eight lines and their movement is provided by one common drive system. The concentration ratio of the design is about 11. Experimental testing showed that the efficiency equals 70% next to the point of optical efficiency (T_{mean}-T_{amb} ~ 0 °C) and the stagnation temperature is 297 °C. The efficiency of the collector was found equal to 43% for an inlet temperature of 100 °C and a direct normal irradiance of 890 W/m².

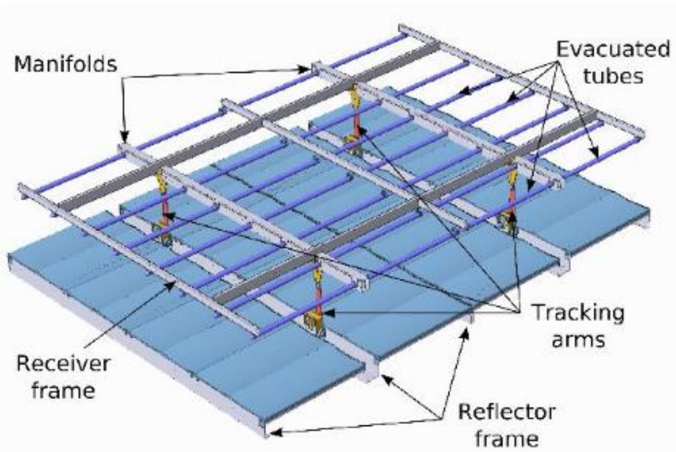


Figure 12: Schematic FMSC design of the CCStaR [22].

Figure 13: Picture of the CCStaR prototype in operation [22].

In his Master thesis John Fenton Rollins [24] explored the design, construction and evaluation of FMSC in 1975 at the Georgia Institute of Technology.
Rollins designed and constructed a FMSC according to the proposed design of Russell [23]. The design consists of long and narrow mirrors at a certain angle on the inside of a reference cylindrical surface.

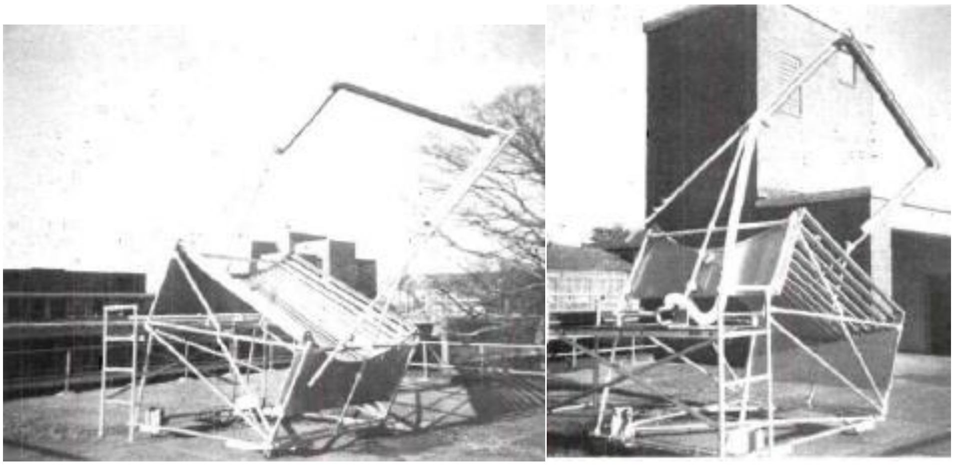


Figure 14: FMSC setup of Rollins [24].

Rolling compared the concentration efficiency based on experimental and theoretical data for different solar angles, as well as the edge losses for different solar angles also. Figure 13 presents solar heat flux charts and compared with theoretical calculations from Russell [23], who is the inventor of this kind of fixed mirror solar collector.

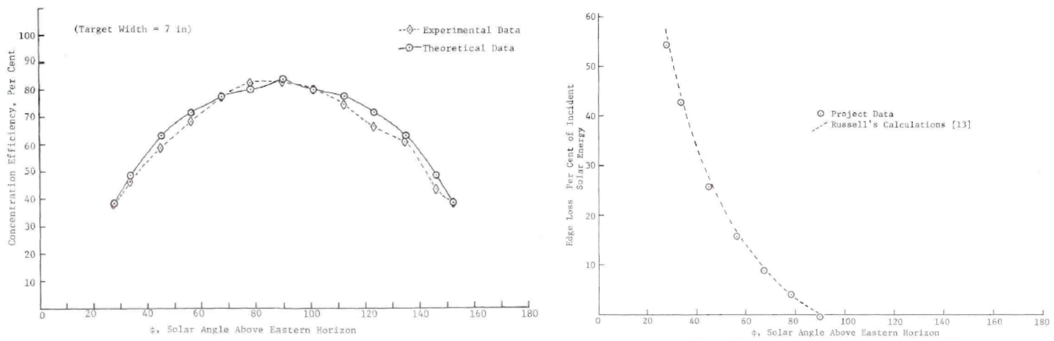


Figure 15: Solar heat flux charts for different angles of the Rollins design [24].

Russell suggested the design of a fixed mirror concentrator [23] and used concrete as support construction of the glass mirrors. Among other things the author states that the heat absorber (receiver) will follow a circular path to remain in focus and practical concentration factors of around 50 can be achieved with a single stage of concentration and80 with a second stage of concentration.

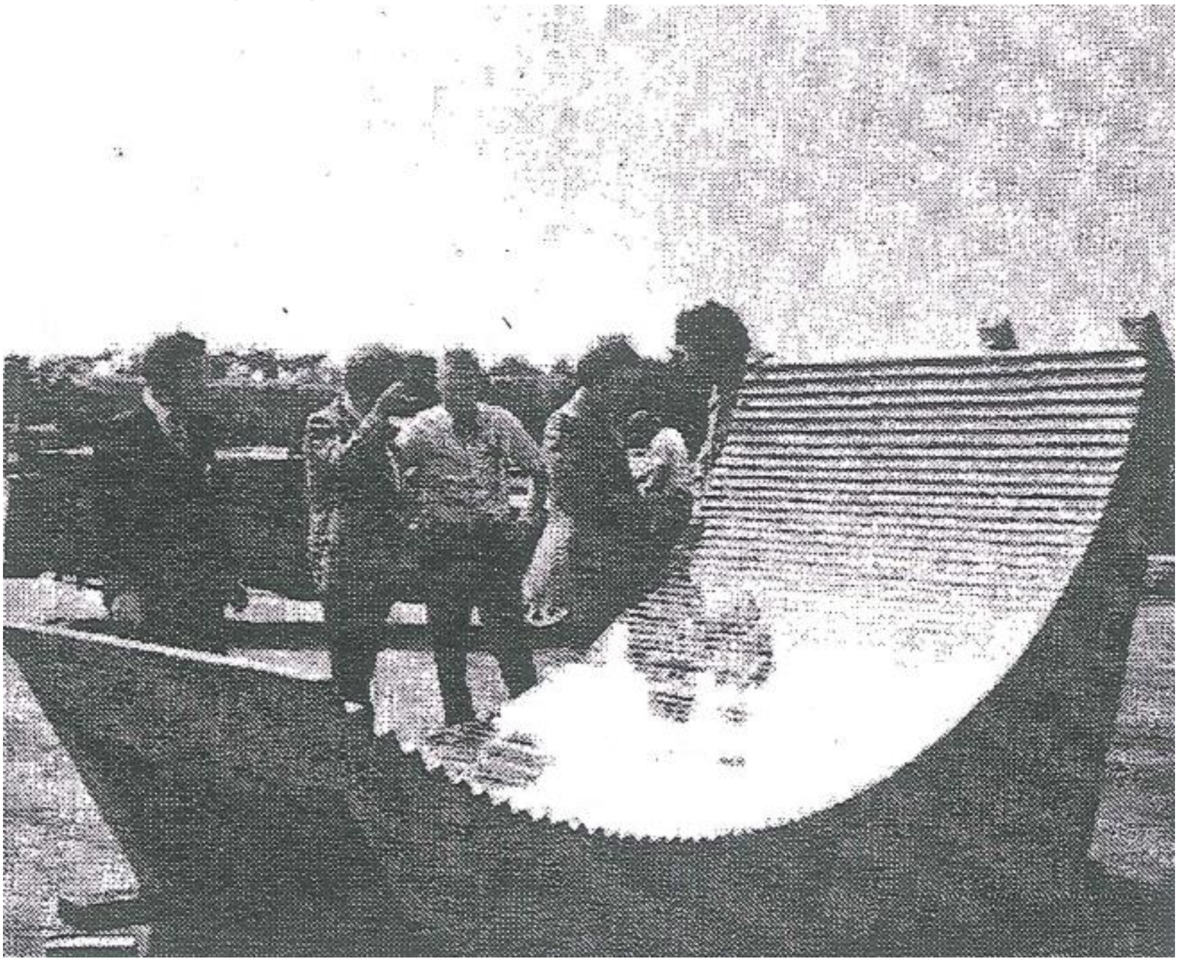


Figure 16: Fixed mirror solar concentrator fabricated with glass mirrors cast in concrete [23].

Russell also holds a US Patent with No. 3,868,823 from Mar.4, 1975 named Concentrator, Method and System for Utilizing Radiant Energy [25]. The invention of Russell is basically the root idea for fixed mirror solar thermal collectors described at [23], [21] and [22]. According to literature and market observation so far, at present no commercial available collector uses this concept.

Also based on the thought of Russell, the Indian researchers Balasubramanian et al. [26] invented a fixed mirror solar collector with curved elements in order to reduce the necessary size of the receiver diameter.

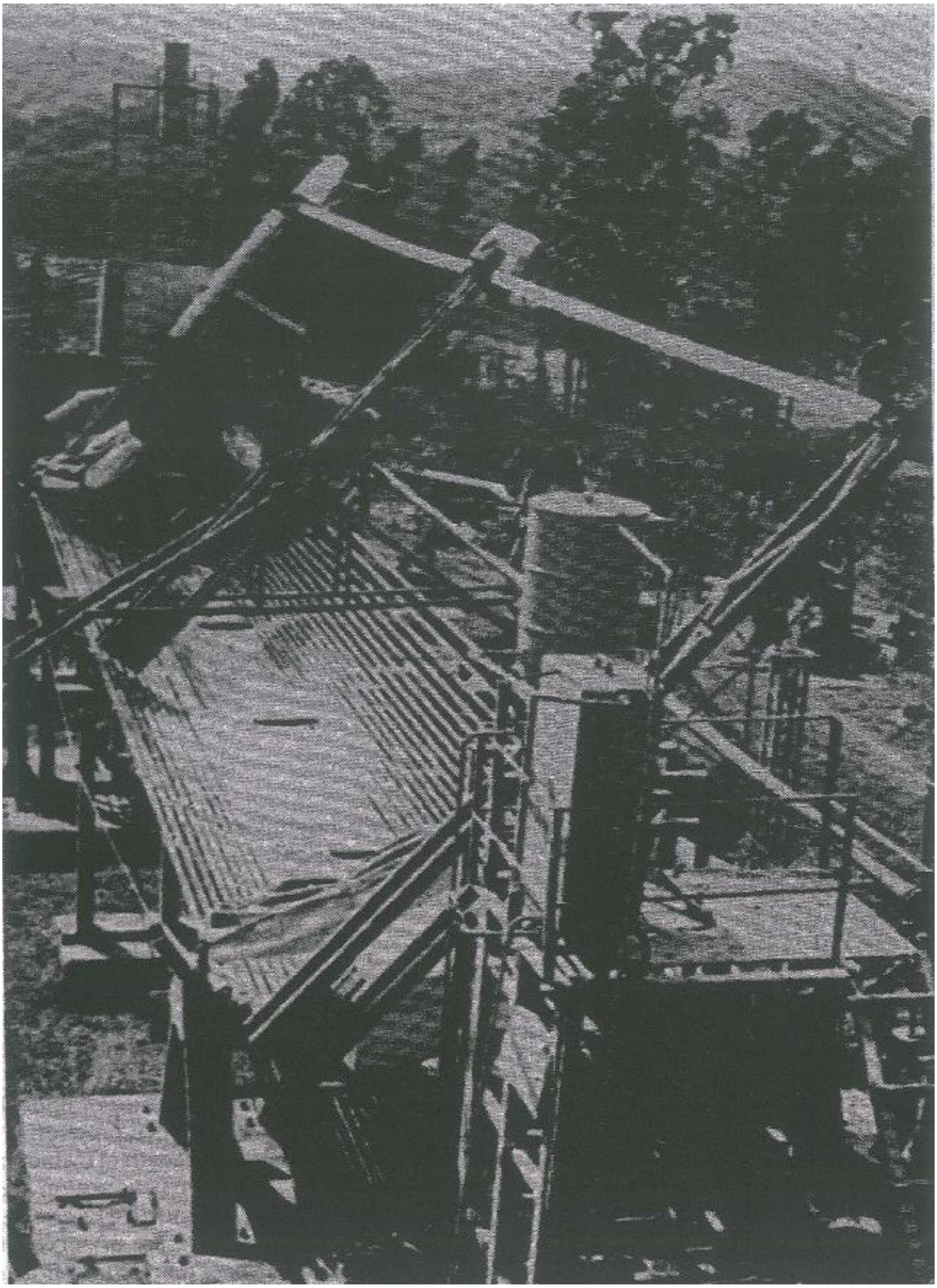


Figure 17: FMSC installed and operated in India / Pune [26].

2.2.2 The UPAT devices

Two systems with concentrator geometry appropriate for the adaptation of evacuated tube collectors have been developed at the UPAT [27] with satisfactory results. The proposed systems' design rests on the general idea to restrict the absorber's thermal losses by limiting the surface area to that with useful energy balance. In order to take advantage of the non- uniform distribution of the concentrated solar energy, the method of division of the absorber is applied. This method has been examined in the past [28] with good results. Utilizing evacuated tubes instead of copper absorber segments, will result in higher operating temperatures and improved system efficiency. The mirror geometry can be adopted on both SCo-1 and SCo-2 models described in the SCoSCo project proposal. The concentrator geometry as well as the absorber characteristics and dimensions of the models tested at the UPAT are presented, in order to provide an idea of the size of the models that will be developed during the SCoSCo project.

Concentrator geometry

The tested models consist mainly of a curved reflector with single glazing and a flat absorber. Two configurations are tested at the UPAT under outdoor conditions, a symmetric CPC and an asymmetric CPC with insulation behind the absorber. A side view of both systems is presented in Fig. 18:

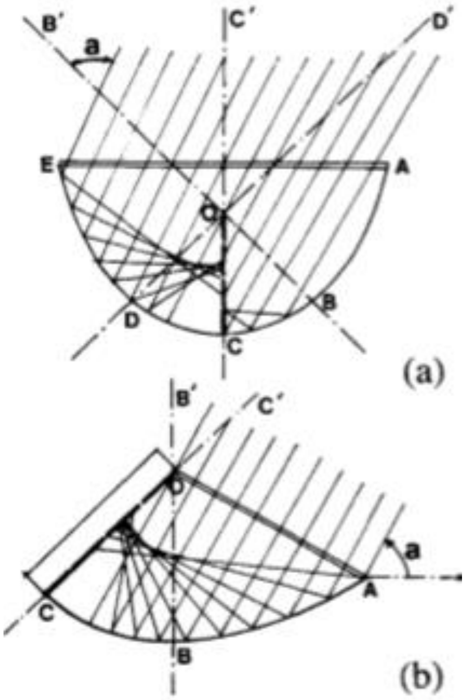


Figure 18: Symmetric (a) and asymmetric (b) systems side view. Source: [27].

The symmetric concentrator consists of a circular section (BD, center O) and two parabolic sections (ED, AB), while the asymmetric CPC consists of a circular section (BC, center O) and a parabolic section (AB). The focal length and radius is equal to the absorber width (OC) for both systems.
As far as concentrator construction and materials are concerned, stainless steel was curved to the geometry described above to form the CPC shape and aluminized mylar (ρ=0.85) was attached properly providing the appropriate reflective surface.

Absorber

The absorber for both systems consists of four copper pipes with copper fins attached on them. The resulting four absorber segments are not in contact with each other.
Selective coating (α = 0.90, ε = 0.15) covers both the pipes and the fins. The absorber surface measures 0.22 m × 1.0 m in total. The technical specifications of the tested systems are shown in Table 2.

Table 2: Technical specifications of the absorbers of the symmetric and asymmetric concentrators.

	Symmetric	Asymmetric
Mirror material	Aluminized Mylar	Aluminized Mylar
Glazing thickness	3 mm	3 mm
Insulation (glasswool) thickness	-	50 mm
Aperture area	0.56 m^2	0.28 m^2
Absorber type	Copper w/ selective coating	Copper w/ selective coating
Absorber shape	Cylindrical w/ flat fins	Cylindrical w/ flat fins
Copper pipe diameter	12 mm	12 mm
Fin width	55 mm	55 mm
Absorber length	1000 mm	1000 mm
Absorber width	220 mm	220 mm
Absorber area	0.44 m^2	0.22 m^2
Absorber fluid	water	water
Acceptance angle	90°	90°
Concentration ratio	1.273	1.273
Stagnation Temperature	>180 °C	>180 °C

Having in mind that the overall system size depends on the absorber size, the SCo-1 and SCo-2 prototypes can be designed around commercially available evacuated tube absorbers e.g., 1800 mm × 58 mm.

2.2.3 3D-systems ("point focus" or similar to point focus)

Another concept of a FMSC is a fixed spherical concentrator (also known as solar bowl). Started back in the late 70´s there is a handful known applications of this technology worldwide, like the solar bowl in Haifa Israel, Texas USA or Recife Brazil [29]. One of the latest installed big solar bowls was erected in India/Auroville and is operating since 2001. In the concept of the solar bowl a biaxial tracking device with counterweight is used. The bowl with a diameter of 15m provides directly steam for a community kitchen which serves ~1000 dishes/day [29].

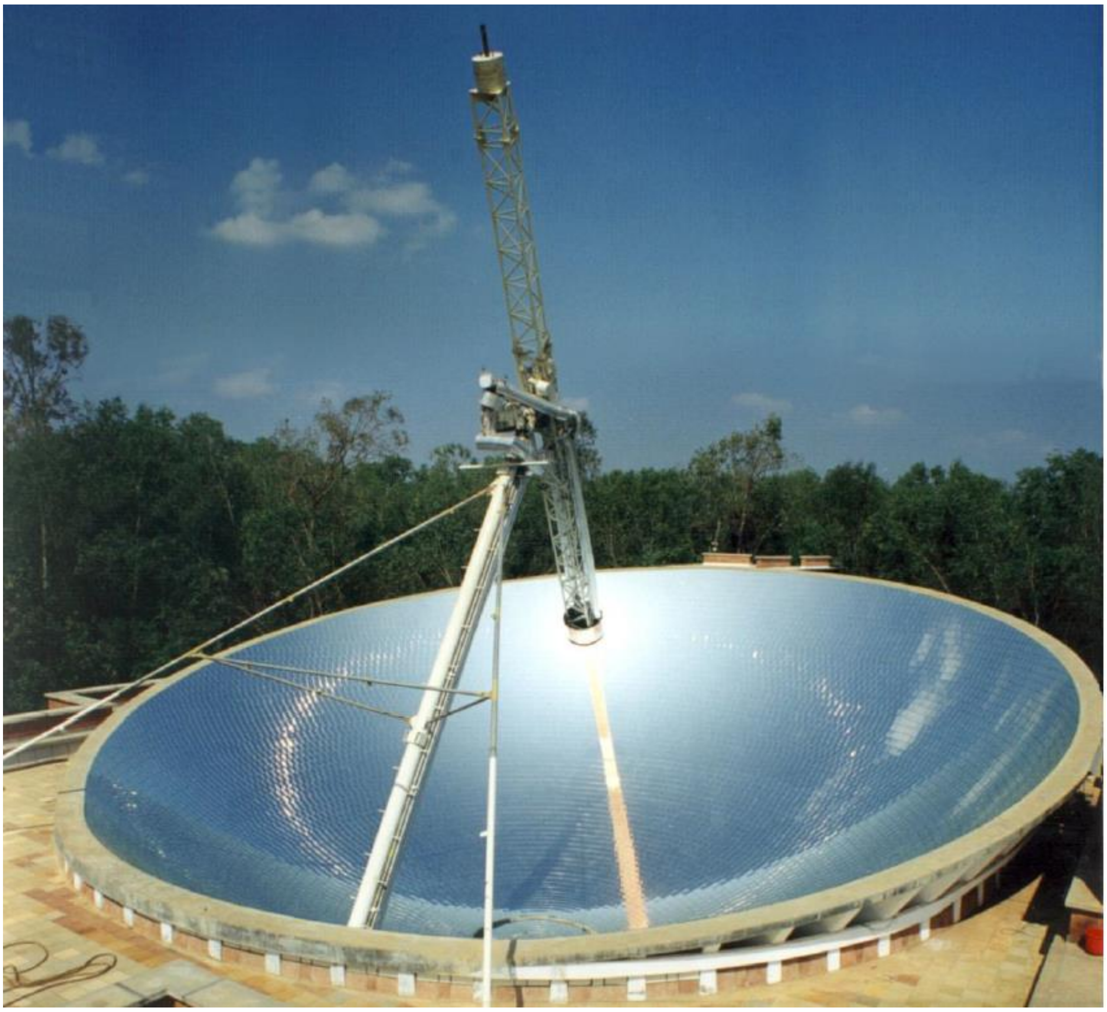


Figure 19: Solar bowl at Auroville/India during operation [29].

Cohen and Grossman [30] applied the spherical concentrator system to a 2.8 diameter modular bowl in 2015. They used 20 mm thick curved steel sheet as accurate reflector shape and lined it with reflective film. They used a cylindrical absorber with black-stove paint and an evacuated glass envelope as receiver element. According to the authors total efficiencies (solar to thermal) of ~50% were obtained for a wide range of temperatures up to 200 °C. The simulations conducted by the authors predict higher efficiencies of approximately 70-80% up to 300 °C depending on the optical properties.

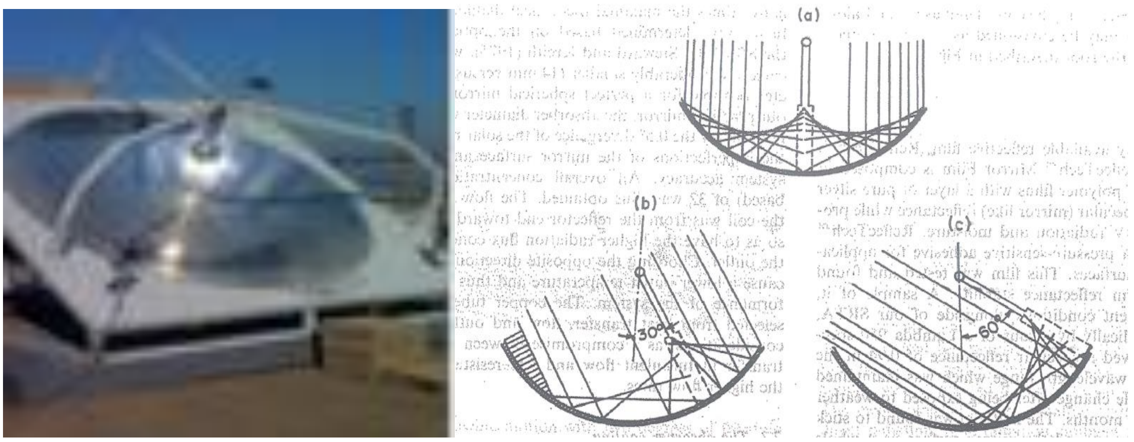


Figure 20: Small solar bowl FMSC installed on roof-top and typical position of the absorber [30].

Table 3: Overview of advantages and disadvantages of FMSC.

Advantages	Disadvantages
Less weight during tracking Reduced torque at drive side	Higher cosine losses
Rate of capacity utilization (area) is better compared to PTC	Self-shadowing (based on design)
Less wind load (if flat design is applied)	Astigmatism at higher IAM
Easier maintenance (if flat design is applied) for cleaning purposes	Higher specific roof area is needed
Possibilities of building integration (Building envelope)	
Lower costs, caused by less weight for tracking	
Best performance at high sun position, good for cooling applications	

2.3 Costs analysis medium temperature collectors

To competitively offer solar process heat applications, low investment costs and low specific solar field costs must be achieved. Forecasts [31] show that the investment costs per collector area for turnkey process heat plants may range between 400 and 700 € /m², depending on the location and the technical application at the consumer side.
Already realized plants worldwide have specific turnkey investment costs between 400 and 650 US$/m² depending on the location and the consumer's technical application [32].

Costs analyses [15] of a 2 m^2_{Ap} collector show that the cost of 650 €/m^2_{Ap} prototype collector is extremely high to compete with regular market prices. A solar process heat collector for the medium temperature range with a high-quality receiver may cost a maximum of 300 €/m^2_{Ap} according to a LCOH method calculation (Levelized Cost of Heat), where the comparison basis had been a Fresnel type benchmark solar system by the company Industrial Solar GmbH.
Investigations in the frame of the project PolyP [15] showed that the construction of the reflector unit, with the mirror and the construction beneath it, may have better properties in terms of a good cost-value ratio. Moreover, it is necessary to increase the aperture width of the collector in order to use the installed receiver more efficiently in terms of receiver costs/$m^2_{Aperture}$. The third cost driver is the tracking unit, since for long lines of collectors a powerful motor/gear system is required as well as a solid support construction [15].
Moll and Schweiger [19] predict 220 €/m^2_{Ap} for a turnkey installation of their FMSC development.
The authors of the BINE brief [33] mentioned for Fresnel type collectors, that there is the major drawback of higher cosine losses and self-shadowing. Moreover, the distance between focus and reflector is larger, which might lead to the use of a secondary reflector. This leads to a reduced energy yield. Therefore, the costs of Fresnel type collectors should be in the range of 71% compared to state-of-the-art parabolic trough collectors. The advantages of the system are the easier construction type, due to reduced wind loads. Moreover, the maintenance work is facilitated, less space is required and the overall economic benefit is given. Typically, Fresnel type systems should cost 70% less than parabolic trough collectors in order to be competitive in terms of collector costs. Since FMSC have also the drawback of the of higher cosine losses, self-shadowing of mirrors and in addition a limited IAM at higher incident angles, the ratio of the FMSC system costs compared to state of the art parabolic through collectors might be even lower.

2.4 Receivers for linear concentrating collectors

Within the project PaRiS [14] the development of a receiver for medium temperature collectors was conducted. The following table shows the data of various receivers available on the market. The list is not exhaustive.

Table 4: Overview of receivers for parabolic trough collectors available on the market [14].

Manufacturer of vacuum receiver		Schott PTR 70	Rioglass UVAC 70 – 7G	HIMIN HSC 3420	PaRiS receiver (planned)
Component \ Country		Deutschland	Spanien/Israel	China	Deutschland
Dimension	Length	4060 mm	4061 mm	3420 mm	2990 mm
	Usable length	~96,7% of total length at 350°C	~96,4% of total length at 350°C	~93,9% of total length at 350°C	~87% of total length at 350 °C Bellows outboard mit: Length: 80 mm Diameter: 110 mm Location: one-sided
Absorber tube	Outer diameter / WS	70 mm	70mm x 2 mm	42 mm x 2 mm	38 mm x 2 mm
	Coating	Selective coating PVD Sputtering	Selective coating PVD Sputtering	Selective coating PVD Sputtering	Selective coating PVD Sputtering [PolyCSP]
	Emissivity (T=??)	ε ≤ 9,5 %	ε ≤ 9,5 %	ε ≤ 11 %	ε ≤ 10 %
	Absorptance	α ≥ 96 %	α ≥ 96,2 %	α ≥ 95 %	α ≥ 95 %
	Material support tube	Edelstahlrohr DIN 1.4541	k.A.	DIN 1.4401	DIN 1.4541
Glass tube	Material	Borosilicat	Borosilicat	Borosilicat	Borosilicat
	Outer diameter	125 mm	115 mm	102 mm	70 mm
	Antireflex coating	Yes	Yes	No	No
	Transmittance	τ ≥ 97 %	τ ≥ 96,7 %	τ ≥ 92,0 %	τ ~ 92,0 %
Thermal losses		250 W/m [at 400 °C]	k.A.	170 W/m [at 400 °C]	250 W/m [at 350 °C]
		165 W/m [at 350 °C]		113 W/m [at 350 °C]	180 W/m [at 300 °C]
		110 W/m [at 300 °C]		71 W/m [at 300 °C]	110 W/m [at 250 °C]
		70 W/m [at 250 °C] Data from product data sheet		48 W/m [at 250 °C]	75 W/m [at 200 °C]
				29 W/m [at 200 °C]	[kl. Ringspalt]
Operation temperature	Maximum	400 °C	400 °C	400 °C	350°C
Vacuum	Annular gap	Yes	Yes	Yes	Yes
Gas pressure	absolute	≤ 10^{-3} mbar	≤ 10^{-4} mbar	≤ 10^{-4} mbar	≤ 10^{-3} mbar
Heat transfer fluid	Medium	Conventional HT heat transfer oil, silicone HTF or water			
Operation pressure	absolute	≤ 41 bar	≤ 40 bar	≤ 40 bar	≤ 40 bar
Retail price	Appro.* per tube	800 – 1000 €	800 – 1000 €	500 €	300 € target price

*) Product price is highly dependent on the quantity ordered / produced (economies of scale); listed here as orientation values.

2.5 Tracking units

Tracking units are necessary for highly concentrating collector systems, since the associated acceptance angle becomes smaller. According to Buttinger [34] stationary CPC collectors are used efficiently up to a concentration ratio of roughly 3. Very often the shape of the CPC is truncated in order to achieve a higher acceptance angle.
Generally, there are two major tracking methods; one that uses a sensor and another using an algorithm based control unit. It is also possible to develop a tracking system combining both methods. An example of a sensor-based tracking unit is installed at the SIJ test facility for performance testing.

Figure 21: Sensory based tracking unit with two small PV units and the control box [14].

Algorithm-based tracking units calculate the position of the collector according to a certain location, installation setup and the time. Commonly used algorithms to calculate the current collector position in dependence of the sun position are NREL SOLPOS, DIN 5034 and SUNAE [35].
Since the tracking accuracy has a huge impact on the collector performance, especially when the acceptance angle is small, technical equipment to control the tracking behavior of a collector are necessary.
For this reason, the SIJ uses a so-called Heliosensor. The sensor must be installed exactly on the aperture area of a collector in order to measure the deviation of the aperture area from that of the beam irradiance. The sensor, produced by the company PSE AG, has a positioning accuracy lower than 0.05° within the measuring range of ± 15°, and ± 0.5 % at larger angles of incidence [36].

Figure 22: Installed Heliosensor in the aperture area of a collector (detail (left) and general view (right)) [14].

Table 5: Overview technical specifications of the Heliosensor.

Acceptance angle	± 55°
Resolution	better than 0.02°
Accuracy	better than 0.05° (for the measurement range ± 15°), better than 0.5 % for the entire acceptance range
Temperature range	-20 °C to +60 °C
Data interface	Ethernet
Communication protocol	Modbus TCP
Power supply	12 – 24 V DC
Power consumption	2.4 W
Size	diameter 95 mm / height 35 mm

A sun-tracking control system called ORSYS [37] has been proposed for a FMSC and tested on the CCStaR prototype. The proposed tracking system controls the receiver's position, relying on a two-step algorithm, the first one for coarse adjustment based on solar time, and the second one for fine adjustment based on a radiation sensor.

3 Process heat applications of medium temperature solar thermal collectors

3.1 Thermally Driven Chillers

Solar-assisted cooling and air conditioning is a process in which solar energy directly supplies the energy for cooling and air conditioning [38]. Solar cooling is divided into two broad groups, which is the solar-thermal cooling with heat pump and solar electricity cooling by using Photovoltaic (PV) to drive conventional motor-driven compression chillers. The principles of solar-assisted cooling and air conditioning can be seen in Fig. 23.
However, this survey will only focus on the technology of solar-thermal cooling systems with thermally driven chiller.

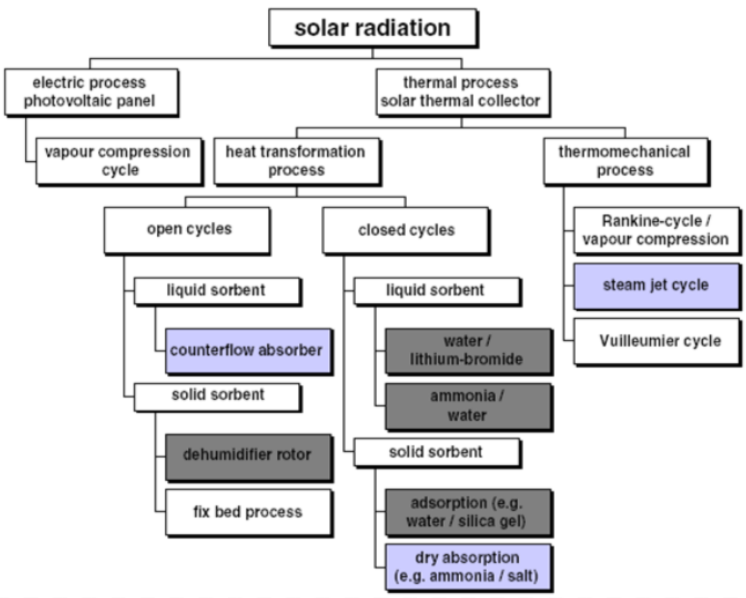


Figure 233: Principles of solar-assisted cooling and air conditioning [39].

There are many different types of solar-thermal chiller systems. Absorption chillers are most frequently used in solar cooling systems [38] [40] [41] [42] [43] [44]. Out of 70 solar-assisted cooling

systems in Europe, 59% of them use absorption chillers [43]. As of now around 1 000 solar cooling systems have been installed and 70% of the total installed systems are absorption chillers [45]. This is because there are many available inexpensive, low-grade heat sources, such as solar heating, industrial waste heat and waste heat from cogeneration plants [38] [43] [46].
An absorption chiller system is classified according to its working temperatures and the thermal efficiency which is described by the coefficient of performance (COP). Current available technologies for solar cooling purposes are single, double and triple-effect chiller systems. A higher driving temperature around 95-135 $^{\circ}C$ is needed to operate double-effect absorption chillers. Thus, the driving temperature of 100-150 $^{\circ}C$ for solar collector in this study is significant to operate the chillers. The refrigerants are thermally compressed by using a refrigerant/sorbent solution and a heat source. As of now, the typical refrigerant and sorbent pairs used in absorption chillers are $H_2O / LiBr$ and NH_3 / H_2O [38] [41] [43]. Many research papers recommended the usage of $H_2O / LiBr$ for air-conditioning, whereas NH_3/H_2O has the advantage of achieving temperatures below 0 $^{\circ}C$. It is recommended for medium-temperature solar collectors (around 150 $^{\circ}C$) to use double-effect Li-Br-water chillers with a COP of around 1.2 for air conditioning [40].
Adsorption chillers normally use solid sorption materials instead of liquid solutions. Market-available systems use water as refrigerant and silica gel as sorbent. Other alternatives for sorbents are porous materials, such as zeolite and activated carbon [47].
The usage of an open cooling cycle with liquid desiccants as an alternative to conventional closed-cycle absorption chillers was suggested in the research paper of Gommed and Grossman [48]. The refrigerant in this system is water, which is in direct contact with the atmosphere, thus it can produce directly conditioned air [38] [43]. Both adsorption chillers and desiccant systems operate on the principle of adsorption. The only difference is that a desiccant system is an open system because the refrigerant, water, is in direct contact with the atmosphere. This system can be further broken down into two categories which are solid sorption using rotary desiccant wheels and liquid desiccant cooling systems. The sorbent, silica gel or lithium chloride is embedded in the solid matrix of the sorption wheels [38].
Steam jet cooling system is currently only used for very few industrial applications in a very high output range. The steam jet cycle is similar to conventional vapour compression cycle, except that the compressor is replaced by a liquid feed pump, a boiler and an ejector vacuum pump [49].

3.2 Solar Cooling Applications

Solar-thermal collector systems can produce driving heat for either cooling or heating or both. This section will discuss simulation and experimental studies regarding solar cooling for commercial and industrial purposes.
Liu [50] simulated a model of a 14kW double-effect $LiBr/H_20$ absorption chiller in Simulink to predict the influence of the external conditions on refrigeration capacity. The result showed that changes in mass flow rate of cooled water has no effect on the performance.
Pedro J [51] ran a TRNSYS simulation of a 17.6 kW $H_2O / LiBr$ single stage absorption chiller with a 1000 l heat storage tank. A $38.4m^2$ flat plate collector was used and a COP of 0.691 was reached.
Assilzadeh [52] performed a TRNSYS simulation for Malaysia weather based on solar absorption cooling system. An evacuated tube collector was used, and the result showed a need for optimisation.

The system is optimised by using a 1-tonne[1] chiller with 35 m^2 of collector, tilted at 20° to horizontal and a storage tank size of 0.8 m^3.

Ming Qu [53] investigated a small solar-thermal cooling and heating system at Carnegie Mellon University. The linear parabolic trough solar collectors of 52 m^2 are connected to a 16 kW double-stage, $H_2O/LiBr$ absorption chiller. The simulation results gained from TRNSYS were analysed and a sizable storage tank was suggested to be installed in the solar collection loop. Moreover, the result showed that the collector orientation had significant influence on the collector performance.

Tiago Mateus [54] evaluated the potential of integrated solar absorption cooling and heating systems for building applications by using TRNSYS as a simulation tool. The result showed economic feasibility for the installation in single-family house and hotel, but the cost of the chiller and solar thermal system need to be reduced.

Palacin [55] designed a simulation model in TRNSYS of a 4.5 kW single-effect, air cooled, $H_2O/LiBr$ absorption chiller. The system used two heat rejection methods which are the dry cooling tower and geothermal sink. On one hand, it was found out that outdoor temperature highly affected the COP. On the other hand, the geothermal sink improved the performance and is independent of outdoor temperature.

C. Monne [56] ran a dynamic model simulation in TRNSYS of a 4.5 kW single effect, rotary $H_2O/LiBr$ absorption chiller with a dry cooling tower.

Other than simulation studies, there are already available installation of solar cooling for commercial and industrial purposes as shown in Table 6.

[1] The equivalent of 1 tonne is 12,000 Btu/h or 3.517 kW

Table 6: Installation of available thermally driven chiller.

Installation	Specifications	Result(s)
Wine Warehouse [57]	**Climate:** Banyuls / France **Cooling System:** Absorption Chiller with 52kW cooling capacity **Absorber Type:** 130 m^2 evacuated tube **Main Application Area:** Cooling of a wine store	Operated more than 13 years without any problem
University Hospital [58]	**Climate:** Freiburg **Cooling System:** Adsorption **Collector Type/Area:** vacuum tubes/167 m^2 aperture **Collector Orientation**: 30° and 45°, south **Main Application Area:** 1. Summer: Air Cooling 2. Winter: Support laboratory heating	Thermal COP of 0.42, solar coverage of total heat input for both cooling and heating: 28%
Office and Seminar Rooms [59]	**Climate:** Freiburg **Cooling System:** Liquid Dessicant/Lithium Chloride **Collector Type/Area:** Flat plate/16.8 m^2 aperture **Collector Orientation:** 30 °, south **Main Application Area:** Solar Cooling in summer and solar heating in winter	Average COP of 1.0

The literature study based on the simulation showed that absorption chiller with a storage tank is preferred regarding solar thermal cooling systems.

4 Conclusions

According to the market assessment of the authors on FMSC, no collector of this type is available as an of-the-self product. For an FMSC (CCStaR [22]) a collector manufacturer is mentioned, but nowadays there is no further information available and the mentioned webpage is not working either.
An FMSC is in operation at a community canteen in India, where prices for workforce is rather low and the extra effort for construction of such a system might be meaningful compared to conventional systems. Moreover, the architectural concept and aesthetic reasons may also stimulate the installation of an FMSC system. Another reason to choose an FMSC might also be just to showcase the technology. Due to the lower performance of an FMSC, caused by a higher cosine factor, an astigmatism that occurs at higher IAM and higher spillage losses, such a system has to achieve a price advantage at the investment costs in comparison to linear-focus systems with the same aperture area and operating temperature. Moreover, the self-shadowing of some design concepts of FMSC reduce the efficiency and the yearly yield of those systems and have to be considered. Also, the roof area used for the installation might be a crucial factor, during a techno-economic evaluation. Depending on the application, an FMSC might have a good matching between heat supply and demand for solar cooling applications.

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