SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Task 53
New Generation Solar Cooling & Heating Systems (PV or solar thermally driven systems)

Solar Heating and Cooling & Solar Air-Conditioning

Position Paper

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Contents

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Solar Cooling – Position Paper

The purpose of this paper is to provide relevant information to energy policymakers so that they can understand why and how solar cooling and air-conditioning (SAC) systems should be supported and promoted. It presents state of the art solar thermal and photovoltaic supported solar heating and cooling systems. In addition, it provides a comprehensive summary of the main findings as provided by the IEA SHC Task 53 work.

Executive Summary

Space cooling is and will continue to be one of the most critical issues in energy systems[1]. Increasing demand for refrigeration and air conditioning has led to a dramatic increase in peak electricity demand in many countries. In addition to rising electricity costs, brownouts in summer months have been attributed to a large number of conventional air conditioning systems powered by electrical energy. The increasing usage of vapor compression cooling machines (more than 100 million units of room air-conditioners were sold in 2016 worldwide) also leads to increased greenhouse gas emissions from indirect emissions related to fossil fuel derived electricity consumption.

An opportunity to reverse this trend is to use the solar source, that produces the cooling demand in buildings. The distinct advantage of the cold production based on solar energy is the high contemporaneity of solar irradiation and cooling demand (i.e., the use of air conditioning is highest when sunlight is abundantly available), which reduces the need for energy storage.

Solar cooling consists of two main solutions (i) photovoltaic systems in combination with vapor compression cooling machines, and (ii) solar thermal systems in combination with thermally driven sorption chillers, both solutions are market-ready technologies. The IEA Solar Heating and Cooling Program (IEA SHC) provides an overview of the state-of-the-art technologies and markets. Market barriers and innovation challenges are identified as well as suggestions to overcome them.

Significantly hot summer periods in Europe, as well as the use of natural refrigerants, has increased the awareness of solar cooling technologies in the industry. More than 1,500 solar cooling systems have been commissioned in recent years, mainly based on solar thermal collectors and thermally driven chiller[2] utilization. Interest in these products continues to increase.

As costs related to generation and distribution of electricity during peak periods remain high and more frequent electricity blackouts occur, the attractiveness of

[1] OECD/IEA (2018): The Future of Cooling. Opportunities for energy efficient air conditioning. Edited by IEA Publications, International Energy Agency.

[2] Mugnier, Daniel; Jakob, Uli (2015): Status of solar cooling in the World. Markets and available products. In WIREs Energy Environ 4 (3), pp. 229–234. DOI: 10.1002/wene.132

solar cooling systems will continue to grow.

The technological development of solar thermally driven cooling has significantly advanced in recent years. As a result, the focus of research has shifted towards addressing the challenges that pertain to the system level in proper design and operational control of fully integrated systems. The same occurs with respect to the PV driven solutions which often use market available, reliable components that are assembled and complemented with low-priced PV modules.

Integrated systems that maximize the share of consumed solar energy is the only way to significantly decrease pressure on the electricity grid.

Unfortunately, solar cooling has not yet been sufficiently developed to reduce costs effectively. To fulfill its environmental and cost reduction potential - widely based on innovations and market sales increase - solar cooling will likely require some form of government policy support in the short term. Policy mechanisms should include both thermal and compression driven systems so that solar heating and cooling can share support policy targets accordingly.

Regardless of the support scheme (e.g., direct grants, tax incentives, minimum building renewable energy content), it is most important to avoid stop-and-go support, which usually harms the market more than it helps.

Both, public and private R&D efforts are needed to further improve solar cooling at the system level. Research and development should focus on pre-engineered systems for the medium capacity range, which minimizes design and planning effort, and the risk of installation errors. Simplification of the systems is key to reach a wide range of applications.

Specific focus on quality procedures for design, commissioning, continuous measurement, verification and maintenance of systems.

Introduction and Relevance

A major argument for solar-driven systems is that they consume less fossil-fuelled energy and often use natural refrigerants. In Europe, their utilization is also encouraged by the European F-gas regulation No. 517/2014. Another driver for solar cooling technology is its potential to reduce peak electricity demand, particularly in countries with significant cooling needs and grid constraints. Solar energy can be converted into useful cooling by two main principles:

1. Electricity generated with photovoltaic modules (PV) can be turned into cooling using well-known refrigeration and air-conditioning technologies that are mainly based on vapor compression cycles.
2. Heat generated with solar thermal collectors (ST) can be converted into cooling using thermally driven refrigeration or air-conditioning technologies. Most of these systems employ the physical phenomena of sorption in either an open or closed thermodynamic cycle.

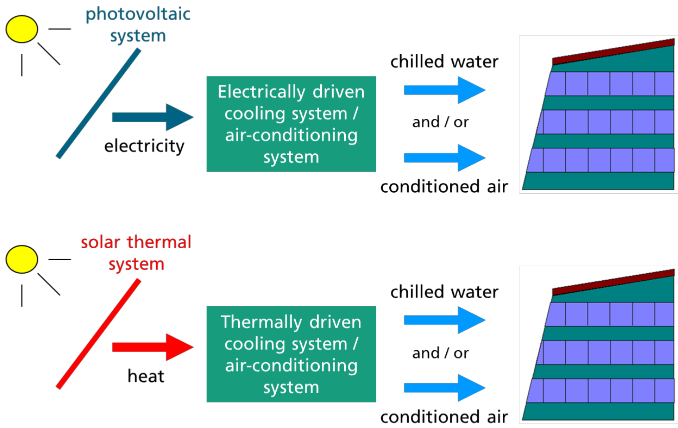

Figure 1: Principles for solar driven cooling. (source: Fraunhofer ISE)

IEA SHC Task 53 considered both solar PV and solar thermally driven solutions. These new generation solar cooling systems were analyzed and assessed and their technical and economic potential presented.

Solar PV driven air-conditioning is beginning to emerge through the small size segment (split air-conditioners) in Asia. However, if such a system allows PV generated electricity to be significantly exported to the grid, this would not be considered as a "solar cooling system". Such a system is not different to most photovoltaic plants which are connected to the electric grid and operated independently from the heating, ventilation, air-conditioning, and refrigeration (HVAC&R) installation.

Self-consumption-only solar PV driven air-conditioning offer potential benefits to the electricity grid and should be investigated further.

This is particularly favorable in countries where photovoltaic system energy costs are lower than that paid for electricity from the grid.

In 2018, heat driven air-conditioning and refrigeration systems using solar thermal energy as the main driving energy were the dominant technology for solar cooling.

Solar thermal systems, which simultaneously meet the demand for low-temperature heat (for domestic hot water) and high-temperature heat (for air conditioning), are more competitive.

Those combinations are very favorable, especially in moderate climates because they provide a very good year-round balance of solar energy use. Storing solar thermal energy is relatively easy as heat is shifted for cooling supply in the evenings and nights, and moreover storing surplus energy for morning cooling.

Status of the Technology/Industry

In general, solar thermal cooling continued to face challenges during 2016 in key European and Chinese markets. This can be attributed to falling solar PV prices, which allowed cost-effective operation of vapor compression chillers powered by grid-connected solar inverters during daylight and at low fossil fuel prices[3].

In the solar cooling industry, a key focus area has been on reducing costs. Standardization of systems can reduce the investment costs of technologies that continue to be used at too small market volumes. Individually engineered solutions that consist of several components generally result in high costs. Manufacturers from around the globe have responded to the challenge by developing pre-engineered solar cooling kits with cooling capacities between 2.5 kW and 40 kW that are suitable for single-family, multi-family, and commercial properties.

In the segment of small and medium-size applications, a new generation of solar cooling systems, either PV or thermally driven, has appeared among existing solar thermal cooling solutions. Unfortunately, a real and significant market has not yet emerged from these innovations. Nevertheless, several SME's are working on solutions to reduce the relatively high system costs, space requirements and the complexity of solar cooling solutions, especially for small-capacity systems.

Several Chinese manufacturers now include a PV option on their units as a support to the main grid supply, even if this add-on renders the overall system to be an expensive air conditioner. The technological status of PV-driven heat pumps is still in its infancy. Although the technology will not be difficult to develop, the industry presently has not significantly focused on coupling photovoltaic energy and heat pumps. In some cases, it leads to autonomous systems that rely on batteries, which is a major barrier in terms of cost and reliability.

Systems connected to the grid but capable of running on a demand-response approach and exploiting inexpensive thermal storage units may be the best solution.

PV driven systems can either be connected with the grid or operate directly with the chiller/heat pump, whereas the compressor needs to be adapted for that variable operation. The systems need to be designed with a control strategy focused on maximizing PV self-consumption. Surplus PV electricity not used for the HVAC system needs to be considered for household electricity, or other purposes.

To reduce stress on the grid at times without radiation and to maximize self-consumption, the systems require thermal or electrical storage capacity. The design and configuration strongly depend on the entire load profile. Best technical and economic results can only be achieved by an integrated system and, if possible, building load optimization.

Solar cooling with thermal absorption chillers with a cooling capacity larger than 350 kW (100 RT) has recently improved significantly in terms of performance, and cost. The economy of scale plays an important role; solar cooling for larger office buildings, hotels, hospitals or commercial and industrial applications have become

[3] Weiss, Werner; Spoerk-Duer, Monika (2018): Solar Heat Worldwide. Global Market Development and Trends in 2017, detailed Market Figures 2016; 2018 Edition. Edited by SHC Solar Heating & Cooling Programme. Available online at http://www.iea-shc.org/data/sites/1/publications/Solar-Heat-Worldwide-2018.pdf, checked on 6/9/2018.

almost or entirely cost competitive under certain climate and energy price conditions.

Solar thermal systems, which simultaneously combine demand for low-temperature heat (e.g., for domestic hot water) and high-temperature heat (necessary to drive solar air conditioning) are even more competitive. Those combinations are very favorable especially in moderate climates, because they deliver an optimum balance of year-round solar energy use, thus ensuring no solar heat is wasted.

Technical maturity and basic successful rules for design

According to the feedback of realized plants, the systematic preparation of a design guide[4] facilitates the introduction of ten high level qualitative key principles. These principles have been critically challenged among SHC experts through a survey conducted at new generation solar heating and cooling plants[5]. If these principles are obeyed and high-quality components are used to assemble SHC systems reliable, robust and economic results can be achieved.

An adapted version of these 10 key principles, modified for PV and solar thermal driven systems arranged in decreasing importance is given here:

- **Principle 0:** Reduce energy demand before using renewables
- **Principle 1:** Choose applications where high annual solar utilization can be achieved
- **Principle 2:** Keep the process flowsheet simple and compact
- **Principle 3:** Use efficient heat rejection units/systems
- **Principle 4:** Minimize parasitic power
- **Principle 5:** Avoid using fossil fuels as a backup for thermal driven systems (especially for single effect ab-/adsorption chillers)
- **Principle 6:** Apply appropriate resources for designing, monitoring, and commissioning
- **Principle 7:** Provide thermal storage capacity and hydraulics in a form that matches the thermal requirements of each energy demand
- **Principle 8:** Minimize heat loss
- **Principle 9:** Avoid over dimensioning of the collectors (ST and PV)
- **Principle 10:** Design the ab-/adsorption chiller for relatively constant operation at near full load

[4] Mugnier, Daniel; Neyer, Daniel; White, Stephen D. (Eds.) (2017b): The Solar Cooling Design Guide - Case Studies of Successful Solar Air Conditioning Design. Berlin, Germany: Wilhelm Ernst & Sohn.
[5] Neyer, Daniel; Ostheimer, Manuel; Mugnier, Daniel; White, Stephen (2018): 10 key principles for successful solar air conditioning design – A compendium of IEA SHC Task 48 experiences. In Solar Energy. DOI: 10.1016/j.solener.2018.03.086.

Energy performance for PV and Solar thermally driven systems

In IEA SHC Task 53, twenty-eight systems have been analyzed, presenting a great variety of different applications in certain locations[6]. The majority are small-scale systems with a capacity (total heating and cooling) below 10 kW. The PV supported systems are dedicated more to small-scale systems, whereas most of the solar thermal supported systems are large-scale, delivering more than 100,000 kWh/a of cooling energy. Medium-sized systems are dominated by heat pump systems in combination with both solar thermal collectors and/or PV systems. It should be noted that, due to the small number of sales, the majority of the analyzed systems, are demonstration systems which can significantly distort economic evaluation (in particular their upfront costs).

The technical and economic assessment focuses on the relative savings of non-renewable primary energy ($f_{sav.NRE}$) as well as the relative levelized costs of energy (CR) against a standardized reference system (air-cooled vapor compression chiller, natural gas backup). The CR/$f_{sav.NRE}$ plot for all results is presented in Figure 2. A trendline summarises all results, showing increasing costs with increased primary energy savings. However, this trend indicates that both technologies, solar thermal and PV supported systems can be cost competitive at lower primary energy savings (i.e., cases with CR < 1). It is also evident that the distribution of the single results is large, thus clustering according to different characteristics can lead to a more in-depth analysis and conclusions.

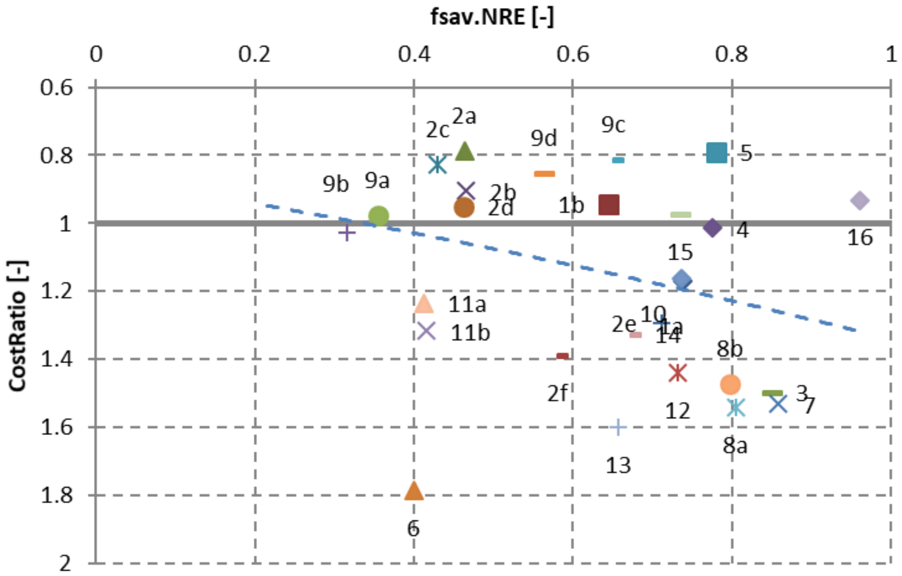

Figure 2: Comparison of the SHC systems in relation to the reference system by levelized costs of energy indicated as cost ratio and non-renewable primary energy savings. Nomenclature: 28 SHC examples (with numbers 1-16 and derivatives a, b, etc.) and its resulting trend line (dashed line) (Köll and Neyer 2018).

[6] Köll, R.; Neyer, D. (2018): Monitoring data analysis on technical issues & performances. Deliverable C3, IEA SHC Task 53. Edited by International Energy Agency.

Economic viability and environmental benefits

In general, the economics of the solar supported systems are investment dominated. Thus, the focus, especially as it relates to small-scale systems, needs to be on reduction of the initial investment utilizing simple installation and compact, air-cooled units. PV supported systems are predestined to a capacity range, as they can be set up with chillers/heat pumps at low costs. However, the convenience and the choice of PV or ST depends on the loads (heating and cooling) to be covered, and the boundaries (quality of electrical grid, etc.).

The investment costs are changed in increments of 15%, from increased costs (115%) to decreasing investments (85, 70%) accordingly. Figure 3 shows the results of changing investment costs on the overall trend of all 28 analyzed SHC plants. The impact of the change is more relevant at higher savings levels.

If initial investment could be reduced by 15% (green) energy savings of 65 % could be achieved with a CR below 1 (levelized cost of energy of SAC lower than the reference system). **If the investment could be reduced by 30% (orange) the levelized cost of energy of the solar driven system would always be lower than the reference one.**

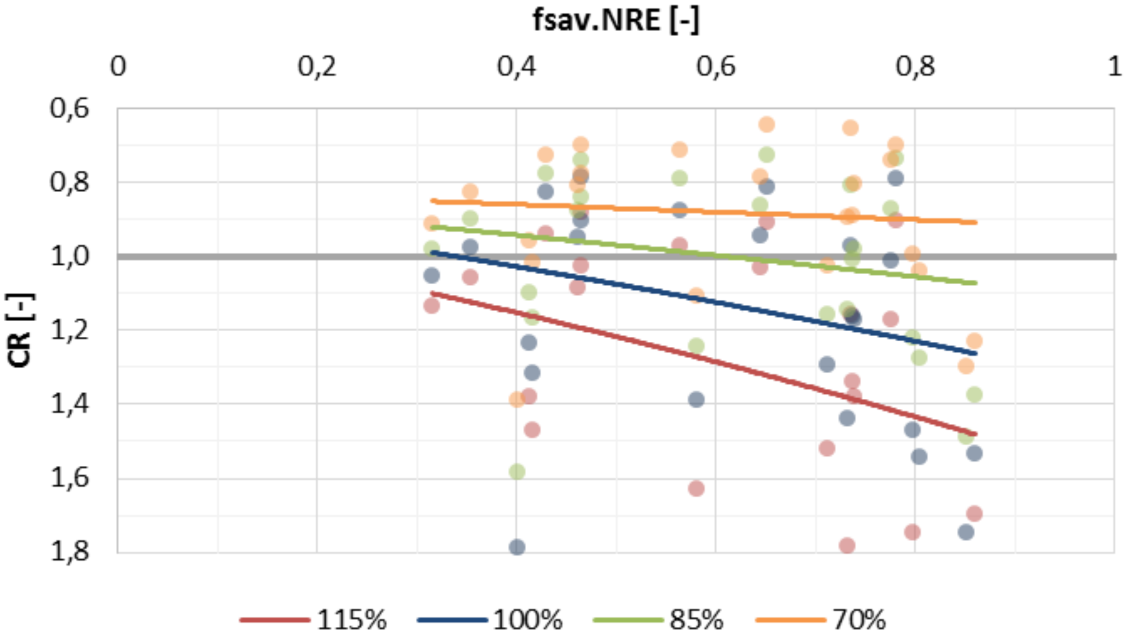

Figure 3: Sensitivity analysis of investment cost for the overall trend.

Market status

Due to the low number of installed SAC systems worldwide, it is difficult to quantify the market status. Relatively few, but highly innovative companies are active in the solar cooling field. This can be split between component manufacturers, system supplier and specialized consulting offices. A few Energy Service Companies (ESCO) are active proposing contracting models for solar cooling for large systems (more than 500 $kW_{cooling}$). The products and status of the companies involved are mainly at the R&D

stage., Commercially active companies/products are rare. The main markets for these players are often in the field of other renewable technologies. For instance, the majority of sorption chiller manufacturers are essentially selling their products in CHP or waste heat-based configurations.

The solar thermal supported components suppliers are mainly targeting; (i) small size compact plug and play units (e.g. Purix, SolabCool, etc.); (ii) hybrid systems combining thermal driven with electrical driven medium-scale components for heating and cooling (R&D) or; (iii) the large-scale size (>500 kW) often including different applications and year around solar utilization.

For photovoltaic driven systems, all manufacturers currently know the possibility of coupling photovoltaic solar energy directly with their heat pumps and have incorporated this possibility into future developments. Large Asian manufacturers such as MIDEA (China), GREE (China), Panasonic (Japan) and LG (South Korea) already have equipment with the possibility of partially integrating photovoltaic energy into heat pumps. In any case, the real integration needs a change of the unit control system in order to maximize the solar contribution.

Potential

The potential for broader market penetration of SAC technology is composed of; (i) further development of the technology in terms of improved component and system performance; (ii) reduction of cost and thus economic improvement and; (iii) identifying preferred applications and business models for the market.

Technical potential

The ongoing R&D on the material level is aimed at improving materials for adsorption and absorption (tailor-made absorbents, e.g., ionic liquids) or absorption cycles and composites mainly using adsorption materials. These materials and compounds have the potential to allow more compact systems with advanced heat and mass transfer and thus lead to lower costs. Work on components includes both advanced cooling cycles and advanced solar collectors, which are tailored to the needs of thermally driven cooling.

The current range of heat rejection units mainly caters for large capacity. The development of heat rejection systems specially designed for use in SAC will lead to reduced component cost, in particular for small capacity units (e.g., below 100 kW of cooling power). These heat rejection units also present limitations in hot and sunny regions of the world where water is expensive and where air-cooled systems are almost inefficient. Further progress and innovation are required in this area.

At the system level, further investigation is required to improve reliability and improve quality in the project delivery chain, ranging from design, planning, construction, and assembly to operation. This work includes measures such as training and education to increase knowledge and experience among professionals active in design and installation of solar supported HVAC systems.

The main potential that can be applied by solar cooling is its high efficiency and low non-renewable primary energy demand. In addition, the use of natural refrigerants decreases the impact on global warming. Systems that are established can be designed for reliable and robust long-life applications. Removal of systems and disposal issues need to be addressed.

The electricity demanded by a solar cooling system, e.g., running pumps and the cooling tower, is quite low. Depending on the climate, electrical SPFs (kWh_{th}/KWh_{el}) of 20 to 40 can be achieved in systems with optimized variable speed drive performances. Thus, the electric demand for air conditioning in a building is cut down by more than 80% compared to conventional HVAC equipment.

Highlights of potentials on the system level are summarized as follows:

- **Adaptation of components** to be compatible with future HVAC systems, that can either be variable speed driven heat pumps/chiller (that provide directly useable cooling/heating) or include storage capacity (if a shift of demand/production is needed).
- **Hybrid components/systems** offer significant potential to allow solar support from ST and/or PV and provide heating/cooling at the same time. This is especially of interest in the tertiary sector where energy demand differs, and the capacity often increases from medium to large scale.
- **Continuous monitoring** to achieve life-long reliable operation. This not only affects solar HVAC positively, but this is also true for conventional systems which often underperform.
- **System simplification** that leads to less complex hydraulics, easier control strategies and to lower heat loss. Overall, a fair reduction in investment cost can be expected, as well as a lower barrier to implement solar supported systems.
- In the small and medium scale range **plug and play, solutions** contribute to the simplification of installation and integration. While plug and play is entering the small-scale market, significant expansion potential exists in the untapped medium-scale market.

Costs and economics

On the component level, the main cost reductions are particularly expected for small capacity cooling machines. Both technology improvements and mass production on an industrial scale will certainly lead to lower costs for these key components. In principle, a noticeable potential also exists for cost reduction of solar thermal collectors, or at least for solar collector installations. However, prices of solar thermal systems have remained relatively steady over the last decade, which can be attributed to unstable market development and market policies.

In general, systems economics are mainly dominated by investment. Thus, the main aim is to reduce these initial costs, but at the same time keeping a high-quality standard for efficient and reliable components. A reduction of overall investment cost by 30% could change the overall economics dramatically. According to the sensitivity analysis presented above, the majority of the system could then provide lower levelized cost of energy than a conventional reference system. If the investment costs decrease, the natural gas and electricity cost becomes more and more a key aspect in the economic equation of a SAC project.

However, levelized cost of energy or total costs of ownership are seldom used to arrive at a decision. The amortization time is more often used to determine the outcome. Currently, 8 to 15 years are realistic if investment costs can be decreased, and in favorable cases, 5 years amortization is possible.

If the economic key performance indicators used in IEA SHC Task 53 ($f_{sav.NRE}$, CR) are considered and used for decision making, it is evident that cost ratios far below one can be reached. Cost savings of 40% during an entire lifetime can be realized. New sales models (e.g., Energy service companies, etc.) need to be developed.

Market opportunities

Generally speaking, the most favorable conditions for successful market implementation of Solar Air Conditioning (SAC) systems are:

- Applications with a high need for heating and cooling (and domestic hot water) or with high and constant cooling need over the year in very sunny regions.
- Locations with high solar energy resources.
- Conditions characterized by a high coincidence of loads and solar gain, since this reduces the need for energy storage.
- Locations with high cost of conventional energy.

A major obstacle is that in many of the locations that fulfill the above requirements, there is no or very little experience of solar energy use, and often HVAC and refrigeration installations are of a comparatively low standard. Nevertheless, under such conditions best economic performance can be expected.

Companies that offer overall solutions and have the capability to provide maintenance services (e.g., using remote control approaches) will be able to exploit this market opportunity.

Overall, renewable energies will play an increasingly important role in future energy systems due to the need to limit CO_2 emissions originating from conventional, fossil energy sources. The need to secure local energy supply to counteract instability in international markets is also a major factor. The demand for Solar Air Conditioning (SAC) technology is significant. This provides a market opportunity for stakeholders including property owners, planners, manufacturers and installation companies.

Current Barriers

Currently, the main technical challenges of Solar Air Conditioning (SAC) lie in system level integration. Many systems fail to achieve planned energy savings because of mistakes in proper design and energy management of systems that result in a high overall electricity consumption of auxiliary components. A particular area where errors occur is the heat rejection subsystem - an area that has often has not received sufficient attention in the past. Other oversights led the development of many systems that were far too complex, and as a result, created non-optimal control resulting in significant maintenance effort.

The main problem areas, observed from practical experience of realized installations, are:

- Heat rejection: cooling towers often need too much electricity and are not properly controlled at part load conditions. Small capacity wet cooling towers are relatively expensive and need an inappropriate high effort for maintenance. Dry cooling towers require significantly less maintenance effort but demand more electricity, and often the heat rejection temperatures are high, which affects system efficiency or disable the use of certain technologies.
- Highly efficient auxiliary components and careful hydraulic design are essential. This is particularly important as solar cooling systems need more hydraulic loops than standard solutions.
- The overall system design requires various professional skills for the different subsystems: solar energy at medium temperature (higher than that used for standard domestic hot water application), hydraulics with pressurized and medium temperature water, and air-conditioning or industrial cooling.

The second main shortcoming of SAC already identified in this paper is the economics. The initial investment costs of realized SAC installations remains at 1.5 to 2.5 times higher than conventional state-of-the-art systems. The two major possibilities to overcome that barrier are; (i) to focus on medium to large system sizes which lead to economies of scale, and; (ii) to standardize as much as possible the systems to reduce on-site effort and risks. An important focus should also be on policy strategies that enable a cost reflective means of internalizing electricity system costs into the upfront purchase price of solar cooling systems.

Currently, the achieved non-renewable primary energy savings or reduction in greenhouse gas emission are not reflected in the economics. Regulations and policies that include the environmental quality could improve economic viability.

Actions Needed

Solar assisted systems are necessary to reach future energy efficiency objectives in the European Union, which set out to reduce 40% of CO_2 emissions by 2030, with at least a 32% share of renewable energy. PV and solar thermal assisted heat pumps are an excellent system to support these targets.

SAC technology is at a crucial stage. Mature components are available, and many installations have been realized. The technology has shown that significant energy savings are possible, and it has reached a level of early market deployment. However, the financial risk for parties involved in SAC business is still too high.

The following actions should lower this risk:

- **Development of systematic quality assurance requirements and standards for SAC systems**: Currently, there are no international ISO/EN standards or norms specifically relating to solar cooling. Such standards would give users the confidence to invest in such systems. They could also provide a basis for allocating funding or tax credit schemes to stimulate market development. These costs for standard developments could be supported by public funding because they create favorable conditions that assist in addressing issues related to CO_2 emissions and climate change.
- **Deployment of specific training for actors involved in SAC projects**: most planners and installers have little experience with SAC technology and thus the effort – and related cost – to install those systems is higher than for standard systems.
- **Implement industry development support schemes that provide like for like incentives for SAC technology and additionally reflect the unique benefits of SAC to the electricity system**: These support schemes support the decision-making process in energy-related investment. And it would help build the market to achieve economies of scale and a competitive supply chain. Collaboration with utility companies to provide them with turn-key solutions to address issues of peak energy demand could be beneficial also.

Develop specific tax credit, tax-free or even funding schemes opportunities for SAC projects (in countries where electricity is highly subsidized, e.g., in some countries of the MENA region). At a national public budget level, electricity savings from related to solar cooling can lead to a reduction in taxation revenue. Measures to support a sustainable market development are most important. This includes establishment of large-scale demonstration programs with both; (i) incentives and; (ii) quality assurance requirements that combine to encourage adoption and lower the risk.

These actions should be organized at regional and national levels. They should first be promoted in regions of the World where cooling is an important issue (e.g., the Middle East, South East of Asia, Sun Belt in the USA, Australia) and where environmental issues are a major concern (such as the impact of pollution due to greenhouse gas emissions).