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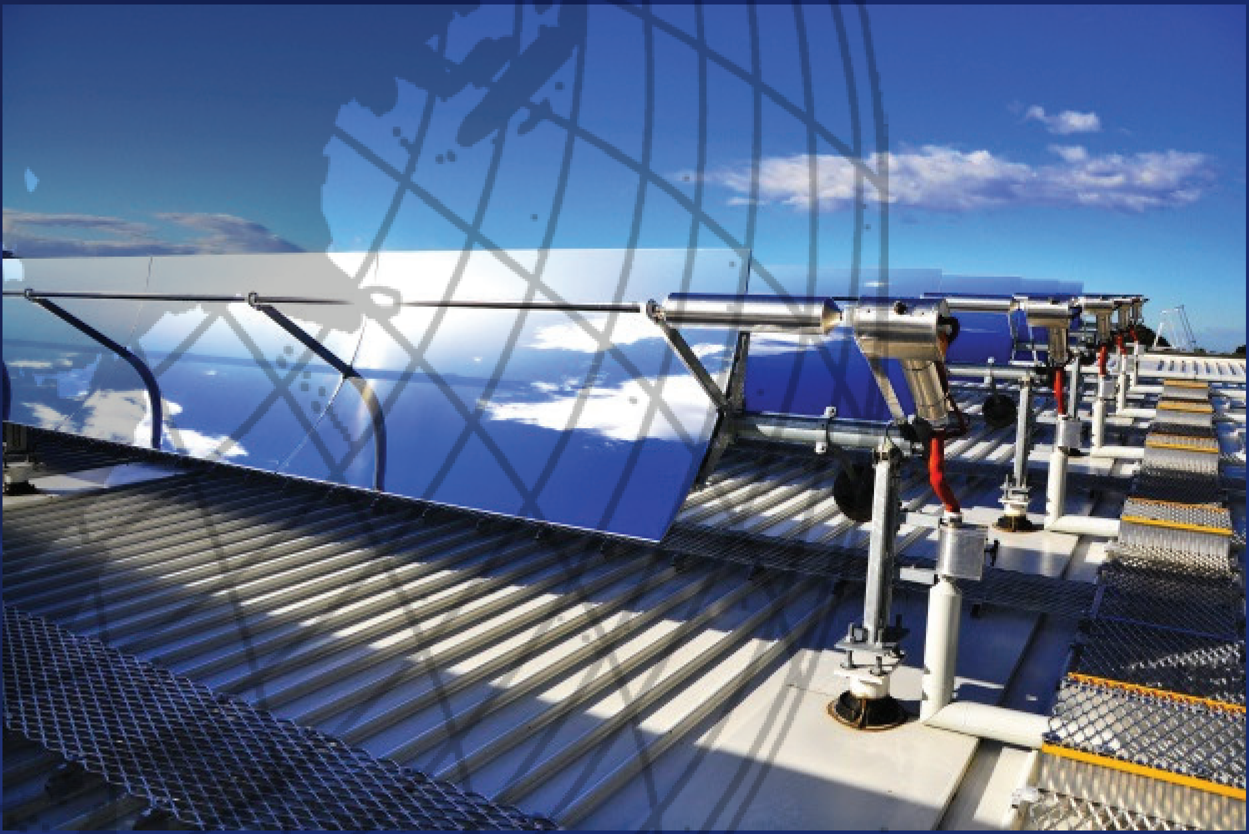
Assessment on the Commercial Viability of Solar Cooling Technologies and Applications in the Arab Region



UNITED NATIONS ENVIRONMENT PROGRAMME

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RCREEE
Regional Center for Renewable Energy and Energy Efficiency
المركز الإقليمي للطاقة المتجددة وكفاءة الطاقة

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NOMENCLATURE/UNITS

Symbols

MW	Megawatt
kW	Kilowatt
W	Watt
kWh	Kilowatt hour
°	Degree
°C	Degree Celsius
K	Kelvin
kg	Kilogram
l	Liter
m^2	Square meter
m^3	Cubic meter
a	Year
h	Hour

Indices

th	thermal
c	cooling
el	electrical

Abbreviations

bar	Pressure
COP	Coefficient of performance
DEC	Desiccant evaporative cooling
DHW	Domestic hot water
DNI	Direct Normal Irradiation
GER	Global energy requirement
GWP	Global warming potential
LCA	Life cycle assessment
LCCE	Levelized Cost of Cooling Energy
MENA	Middle East & North Africa
NPC	Net Present Cost
PCM	Phase change material
PV	Photovoltaic
RES	Renewable energy source
SHC	Solar heating and cooling
VAT	Value added tax

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All cost in this study is given in USD. Please note that cost numbers exclude VAT. The costing is based on manufacturer information and quotes and has an estimated uncertainty of approximately ±30%. All prices are list price and trade discounts are not included.

EXECUTIVE SUMMARY

RCREEE on behalf of LAS and UNEP has commissioned SOLEM Consulting/Germany, assisted by TECSOL/France, to undertake an assessment on the commercial viability of solar cooling technologies and applications in the Arab region. The scope of the study is to create a logical pathway to identify the most efficient, reliable and cost competitive solar cooling technology for the Arab region. Further, the study provides suggestions on how the adoption of solar cooling technologies in 22 Arab countries (Algeria, Bahrain, Djibouti, Egypt, Iraq, Jordan, Kuwait, Lebanon, Libya, Mauritania, Morocco, Palestine, Sudan, Syria, Tunisia, United Arab Emirates, Saudi Arabia, Oman, Somalia, Qatar, Comoros Island and Yemen) can be increased.

For this purpose, two different building types in the Arab region have been defined, with a cooling load of 100 kWc and 1 MWc cooling capacity, respectively. Each building type has been investigated using three different cooling technologies:
a) Double-effect absorption chiller and concentrating collectors
b) Vapour compression scroll chiller and photovoltaic modules
c) Vapour compression scroll chiller and grid operation (reference case)

Net present cost (NPC) as well as Levelised Cost of Cooling Energy (LCCE) have been calculated for each case as part of the comparative analysis.

For the 100 kW_c range, the analysis shows very good results for the following 6 countries:

Favorable countries for a 100 kWc solar cooling system:

Egypt, Jordan, Morocco, Palestine, Tunisia, Yemen.
There, the net present cost over 20 years of lifetime is lower for both solar cooling technologies compared to the reference case. In all countries above, the PV cooling solution is more competitive than the solar thermal one.

For the 1 MWc range, the analysis shows the following results:

Favorable countries for a 1 MW_c solar cooling system:

UAE, Kuwait, Qatar, Saudi Arabia
In the UAE, both solar thermal and solar PV cooling are currently economically viable with lower net present cost than the reference case over 20 years.
In Kuwait, Qatar and Saudi Arabia, solar thermal and solar PV cooling solutions are very close to each other in terms of net present cost. Both solar cooling technologies, however, are only economically viable compared to the reference system if a subsidy of at least 50% is applied on the investment cost.

Based on the economical analysis, recommendations to policy makers for the initiation of solar cooling R&D programs and for linking national R&D efforts with international collaboration programs and projects are presented. A cost estimation of the public budget for proposed actions is presented as well. The **total budget** required for the proposed R&D and demonstration programs will be in total **approx. 4.5 million USD to develop solar cooling for the Arab region:**

Proposed R&D programs and budgets:

1. Development of adapted heat rejection (1.0-1.5 million USD, R&D program),
2. Adaption of existing products/kits to the Arab region (1.0 million USD, R&D program)
3. Development of adapted storage (0.5-1.0 million USD R&D program),
4. 2x 100 kW_c PV Cooling demonstration systems (0.4 million USD, approx. 200,000 USD per project)
5. 2x 1 MW_c Solar thermal cooling demonstration systems (1.2 million USD, approx. 600,000 USD funding for one project)

SCOPE OF WORK

This study investigates the commercial viability of solar cooling technologies in 22 Arab countries to assist a strong and sustainable market development. The study includes:

- Introduction about the status of solar cooling technologies in the world, market status and available products,
- Identifying the commercialized solar cooling technologies at world level and the life cycle analysis at system level adapted for the Arab region characteristics,
- Identification of most economically viable and applicable solar cooling technologies for the Arab world based on expert forecasts, and the expected cost-reduction resulting from R&D and market expansion,
- Identification of international leaders in solar cooling technologies (public and private research institutions and companies),
- Identification of researchers, research institutions and companies in Arab countries that are involved or about to be involved in R&D related to solar cooling technologies,
- Recommendations to policy makers for the initiation of solar cooling R&D programs and for linking national R&D efforts with international collaboration programs and projects,
- Estimation of annual cost to the public budget of proposed actions,
- Recommendations for follow-up.

1. INTRODUCTION

In the introduction chapter the status of solar cooling technologies in the world, market status and available products are examined. For this, the latest materials developed by IEA-SHC Task 48 and Task 53 projects as well as other market surveys on the solar cooling market have been screened. The perimeter of the survey is dedicated to both market available products as well as “close to the market technologies”. Very early stage R&D is excluded. The survey first covers all solar cooling technologies (absorption and adsorption chillers, liquid sorption and DEC systems, PV Cooling using compression chillers) without any judgement on their applicability in the Arab region with its specific boundary conditions. A detailed assessment of the solar cooling technologies suitable for the Arab region can then be found in Chapters 2 and 3.

1.1 Status of solar cooling technologies in the world

Currently, two main solar cooling technologies can be defined:

Solar thermal cooling is a combination of heat-driven ab-/adsorption chillers, desiccant sorption wheels or liquid sorption using solar thermal heat as the main driving energy source (Figure 1). Heat is typically provided using non-concentrating solar thermal collectors, e.g. flat plate or evacuated tube collectors. These are quite common and have a good commercial maturity. Concentrating collectors, e.g. parabolic trough or linear Fresnel collectors are able to supply higher temperatures, however these are not very common for solar cooling applications so far. However, numbers of installations with these collectors are increasing, especially for multi-effect absorption chillers this type of collector is interesting. Most of the concentrating collectors are used in India, Australia and Turkey, because in these countries solar irradiation with a high share of direct radiation is present.

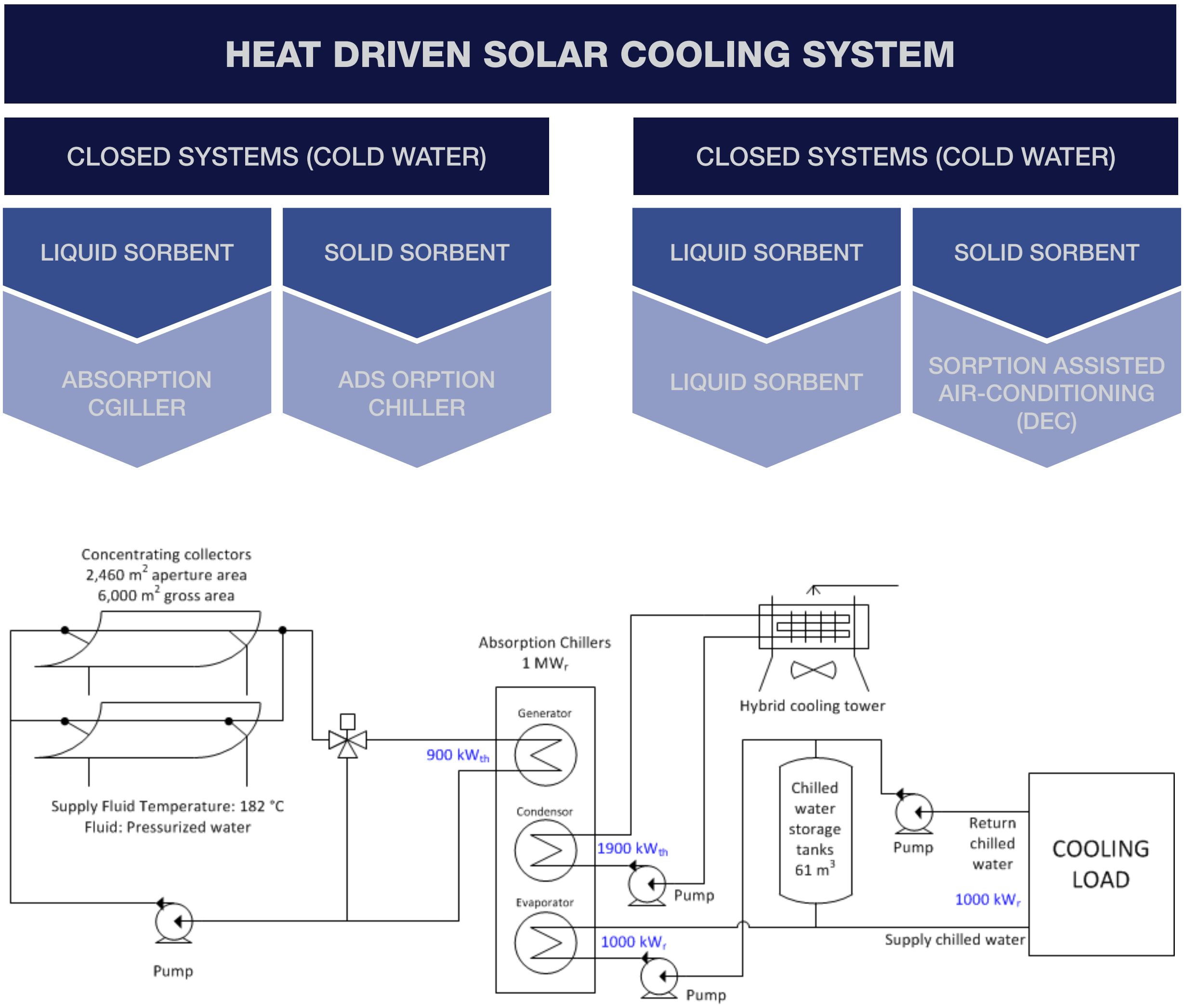


Figure 1: Principle classification and example schematic of heat-driven solar cooling
(Source: Solem Consulting)

In addition to the solar collectors, thermal storage is needed to smoothen to the fluctuations of cooling demand and solar irradiation. Thermal storage devices are market-available in different sizes and various technologies (hot water storage, phase change material (PCM) storage, ice-storage). Both solar collectors and storages are well matured technologies and have a good compatibility, because they are also used to provide domestic hot water or space heating. Further, components for the heat rejection of thermal chillers are required. These differ in their functionality (dry, wet or hybrid coolers) depending on the ambient conditions. They are well-matured technologies and globally market-available. They are also used for conventional vapour-compression chillers.

Different types for sorption chillers and sorption systems have been developed over the last decades. The commercial market for these is some orders of magnitude smaller than their electric counterparts. But, the manufacturing of small heat-driven chillers up to 35 kW_c with a high quality standard has increased a lot recently. Some manufactures have already started production in an industrial scale. The use of larger capacity sorption chillers (35 – 200 kW_c) is not that advanced for solar thermal use, rather for waste heat or gas-fired processes, mostly in industrial applications. Apart from the above mentioned technical components, the boundary conditions, e.g. local energy costs, cooling load hours and the solar radiation, affect the economy of a solar cooling system massively. Care has also to be taken in the planning of such systems, especially with regard to auxiliary energy consumption and system control.

Photovoltaic (PV) cooling is the second technology that uses solar energy to generate cold. It is a combination of PV modules and conventional electrical chillers, e.g. vapour compression chillers (Figure 2). A detailed description on PV Cooling shall be excluded here for reasons of space but can be found in [8]. PV Cooling is currently mainly used in the Asian-Pacific region. There, countries with high cost of electricity offer economically favourable conditions for this technology.

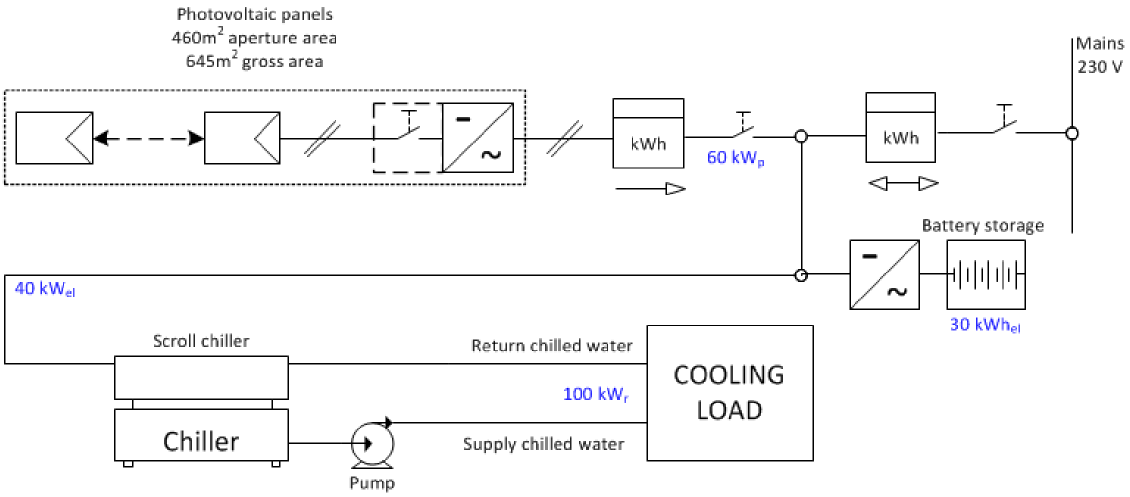


Figure 2: Example schematic of a PV Cooling system (Source: Solem Consulting)

1.2 Market status of solar cooling

1.2.1 Solar Cooling History

The first solar cooling system was built for the World Exhibition in Paris in 1878 and produced ice blocks. Later, the development of solar driven cooling systems for air conditioning was pushed forward in Europe and the USA in the 1980s due to the previous oil crises. With dropping oil prices the market for those early systems dried out again shortly afterwards [1]. The late 90'ies saw the rise of this technology again due to rising oil prices but also increasing cost for electricity and gas.

1.2.2 Today's status of Solar Cooling

The global technical potential for solar cooling is quite large. Globally increasing standards of living as well as climatic changes are drivers for increasing cooling and air-conditioning demand these days. The energy consumption of conventional electrically-driven systems frequently leads to blackouts in hot summers, at least in some regions of the world. Despite increasing costs of electricity, sales numbers of vapour compression chillers and air-conditioners (mostly split units) are growing. Due to that, the market of solar driven cooling systems is also developing, albeit at a much slower rate. The coincidence of cooling demand and high solar irradiation is perfect to generate cold with a natural energy source. Within 10 years (2004-2014) the market growth of solar thermal cooling was about 40-70% with about 1,200 solar cooling systems sold in total (Figure 3). In comparison, the number of split-type air-conditioners sold worldwide is approx. 100 Million per year.

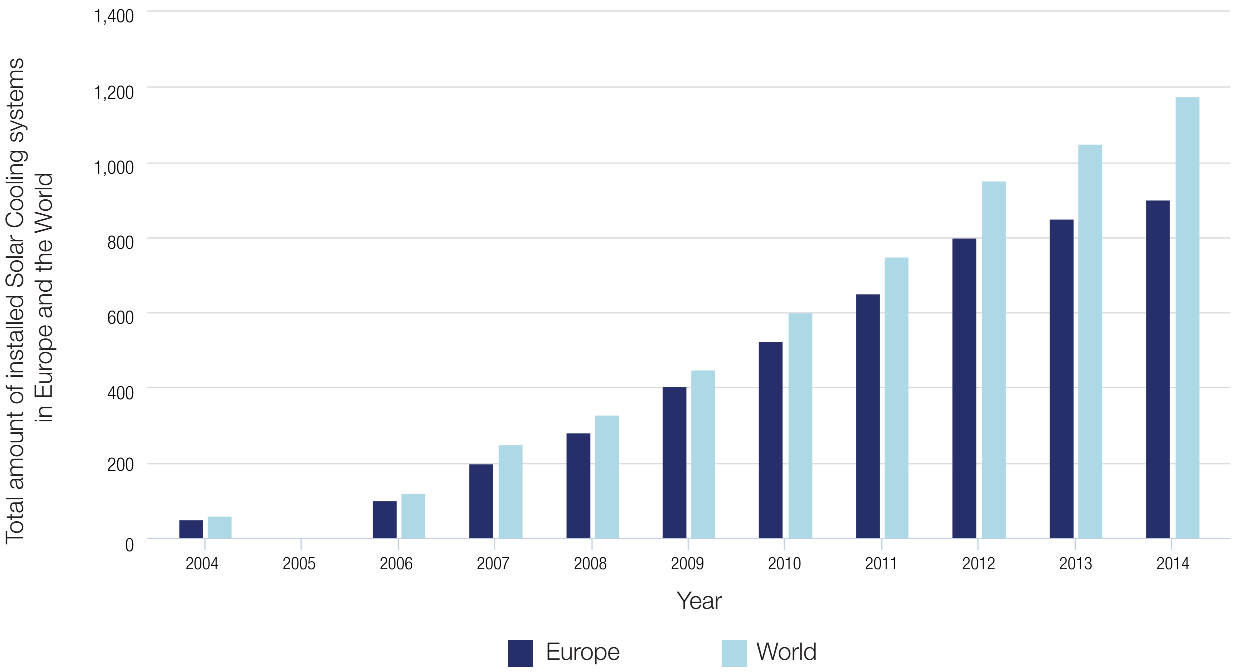


Figure 3: Market development of solar cooling (Source: Solem Consulting / TECSOL)

Solar cooling is still a niche market. As the main reason, the higher upfront investment costs can be mentioned. In comparison to conventional cooling systems, the investment cost for solar cooling is about twice up to five times higher. The cost for solar cooling kits with capacities up to 35 kW_c has been dropped from 6,450 USD per kW_c (6,000 EUR/kWc) to 3,750 USD per kW_c (3,500 EUR/kWc) in about six years (2007-2013), which is a cost reduction by 40-50%. Depending on the region and its specific boundary conditions (energy costs and annual operation time) the ordinary ROI of solar cooling systems is between 10-18 years, nearly equal to the lifetime of 15-20 years [5,6]. But the technologies of this niche market are matured and market ready. Solar air-conditioning for residential buildings up to 20 kW_c is used mainly in Australia, the Mediterranean region, the Middle East and Central Europe [2, 3, 4]

The International Energy Agency (IEA) predicts a market share of about 17% for solar cooling in 2050. To support this, several research tasks on solar cooling have been conducted in IEA's Solar Heating and Cooling Programme (Tasks 38, 48 and 53). One goal of IEA-SHC Task 48 was to enable a sustainable market for solar cooling. An obstacle to achieve this goal is the small production of components for solar cooling systems. To stimulate this development, the support of governments and incentive programs is needed. Other reasons to consider are the dual use of solar heat for cooling and heating as well as not using any storage if the coincidence between solar gains and loads is strong.
Support by continuous incentive programs and standards in several countries should make the way easier. For example, there exist already a large number of support programs in European countries as well as an industry norm in Australia for solar cooling. A view on the different regions of the earth shows that there are many regions that fit with the mentioned requirements for solar cooling. The biggest obstacle is the investment cost, the development and know-how about solar cooling and the availability of the components, which is explained in the next chapter.

1.3 Market available solar cooling products

Solar cooling systems consist of several components. Firstly, solar thermal collectors or PV modules are required. The commercial availability of PV modules around the globe is quite good, the same holds true for the availability of flat plate or evacuated tube thermal collectors. The use of those components is really widespread, because they are easy to implement and frequently used to generate electricity or domestic hot water (DHW). The distribution of the previously mentioned concentrating collector technologies is smaller. This is due to the high temperatures of the collectors which typically can be utilized only for industrial processes with temperature levels above 120°C or to produce steam. Such systems have much lower sales number in general, as they are location and application-specific.

Figure 4 shows the distribution of solar thermal collector manufacturers worldwide. The number of percentage refers to the number of production sites in each continent or country, not to the total produced collector area. The most popular collector types are flat-plate and vacuum tube collectors. Their main markets are in Asia, Europe and North and South America. In general, Europe has a very high density of manufacturers of solar thermal collectors. The database for the flat-plate, vacuum and air collectors is based on an annual report of the solar market [7]. This data was amended using part of the IEA-SHC Task 48 Final report on State of the art on new collectors and characterization (see Appendix 1) [52].

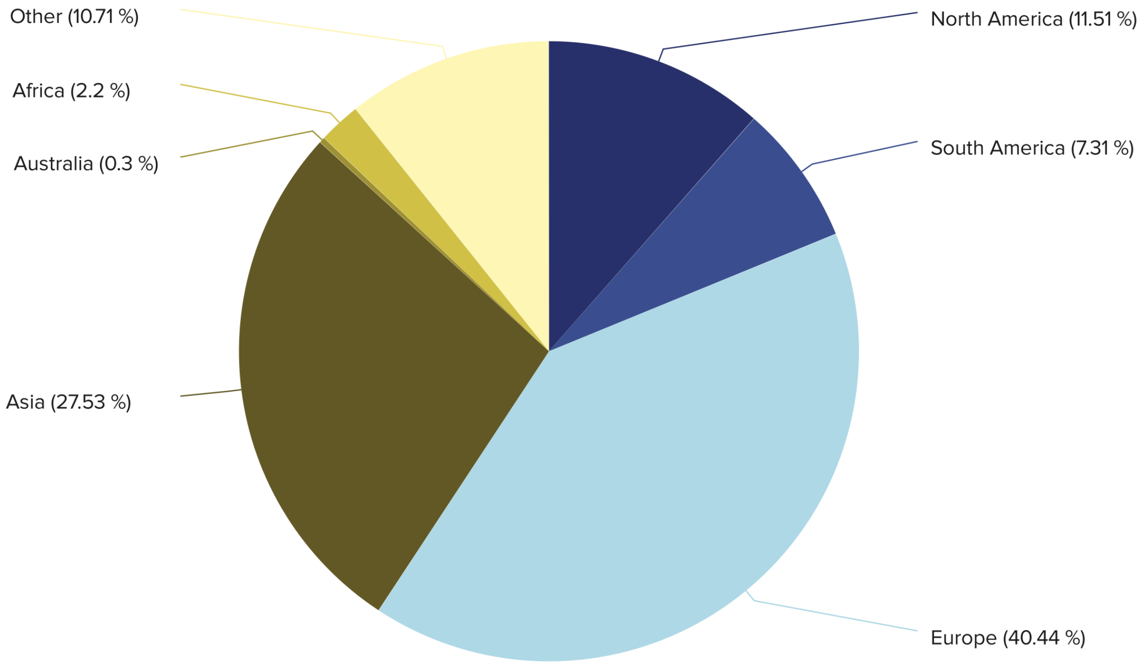


Figure 4: Distribution of solar thermal collector manufacturers (no claim for completeness)
(Source: Solem Consulting)

In the past years, standardised solar thermal cooling systems have been developed as so-called “solar cooling kits” to simplify and standardise the technology and reduce the costs of solar cooling systems. The solar cooling kits offered by the companies generally contain flat-plate or evacuated tube collectors, a hot water storage tank, solar station, pump set, sorption chiller, heat rejection unit and a system controller (Table 1).

Table 1: Supplier of solar cooling kits (no claim for completeness) [8]

Country	Manufacturer	Product name	Nominal Cooling Capacity [kWc]	Technology	Sorbent / Refrigerant
Austria	Gasokol	coolySun	200-15	ABsorption	$LiBr/H_2O$
			15-8	ADsorption	$Silicagel/H_2O$
China	Jiangsu Huineng	Solar central air conditioning	175-11	ABsorption	$LiBr/H_2O$
Italy	Kloben	SOLARTIK	105-17.5	ABsorption	$LiBr/H_2O$
China	Lucy solar	Solar air-conditioning system	175-11.5	ABsorption	$LiBr/H_2O$
France	EDF Optimal solutions	Package system	17.5-210	ABsorption	$LiBr/H_2O$
Germany	SolarNext	chillii® cooling kits	175-15	ABsorption	$LiBr/H_2O$
			100-19	ABsorption	H_2O/NH_3
			10	ADsorption	$Silicagel/H_2O$
			30-10	ABsorption	$Zeolithe/H_2O$
China	VICOT	Solar air-conditioning system	141-17.5	ABsorption	$LiBr/H_2O$

In summary it can be stated that as shown in Figure 4 the solar manufacturers are not located in the regions with the highest potential of solar cooling, but in the leading nations of renewable energies and their technologies. The area of a high solar irradiation is around the equator. Also located in this area is the Arab region with its 22 members.

Secondly, chillers are the other main component of a solar cooling system. They are typically globally available since they are manufactured and distributed by large global companies (the exception are the abovementioned small chillers up to 35 kW_c. These are mainly from Europe, China and Japan). The survey of chiller manufacturers for solar cooling or market ready solar cooling kits (Table 1) shows that those are also limited to a few countries in Asia, Europe and the USA [1]. A geographical discrepancy between the manufacturers of thermal collectors and sorption chillers or cooling kits needs can be noted. This should be improved, because standardized solar cooling kits can reduce the costs of solar cooling for the investors and make it economical more interesting.

A particular case considered are air conditioning technologies using direct expansion of refrigerant. These units, mainly split air-conditioners, are not adapted for being coupled with solar (thermal) technology. A coupling is only possible using PV modules. However, for the typical residential size between 3 to 10 kW_c cooling capacity, the PV panels can only be a partial contributor and very few products are available using battery storage to create a buffer between the solar production and the A/C unit consumption. This leads at the moment to a simple development in the building sector: PV panels used for self-consumption in a net metering approach. The split air conditioners are market-available and usually already installed in a house. If PV panels are installed in addition, in theory a PV Cooling solution is implemented. However, the main part of the solar energy of such a system will be used for other electrical consumers in the house. R&D interest of this approach is equivalent to studying the possibilities of controlling the behaviour of the split unit and be able to store energy as electricity or cold when PV production is not in adequate with A/C unit demand. These topics are questions to be analysed by IEA-SHC Task 53 dealing with a New Generation of Solar Cooling systems and are of interest for the Arab Region.

Main conclusions on solar cooling market:

Solar thermal cooling
Significant progress was made in the last decade. It includes:

the development of new, small scale heat driven chillers < 35 kWc
increasing development of high efficient double/triple effect absorption chillers
the development of single-axis tracking concentrating collectors

The components are available, but the main technical shortcomings of solar thermal cooling can still be found on the cost and system level. There, the main obstacles for widespread market acceptance are:

high upfront investment cost
heat rejection can be difficult in hot and humid countries
planning is individual for larger systems, standardised solutions still missing
well trained technical staff almost not available

PV cooling
Components are market-available. Small systems in a net-metering approach require low effort for planning and installation, however coincidence of A/C demand and solar energy need to be improved using battery storage. The cost for this is currently still high, but expected to drop significantly in the next 5 years. Larger systems require higher effort for planning and installation.

2. TECHNICAL AND FINANCIAL FEASIBILITY ANALYSIS

In this chapter the identified commercialized solar cooling technologies at world level are adapted to the Arab region characteristics. A life cycle assessment (LCA) at system level is presented. The Arab countries all have regional differentiations (climatic conditions, prices etc.). Therefore, a filter has been applied on the results of the market survey given in the previous chapter. The filter includes the individual regional climatic conditions (heat rejection, dust, extreme temperatures) and the direct short-term market availability of components. In order to deal with the LCA at system level for the Arab region characteristics, the IEA-SHC Task 48 LCA approach and method are being used. The above methodology then leads to selected products for the Arab region. Furthermore, the most economically viable and applicable solar cooling technologies for the Arab region are being identified based on real technology cost. For early market / demonstration technologies target prices have been estimated. Finally, an expected cost-reduction potential from market expansion and R&D is calculated.

2.1 Solar cooling technologies for the Arab region

Starting from the detailed analysis of the market available solar cooling products, a specific focus now must be laid on the specific conditions in the Arab region.

The scope of the present study is the group of 22 countries of the Arab region (Figure 5): all the RCREEE member states (Algeria, Bahrain, Djibouti, Egypt, Iraq, Jordan, Kuwait, Lebanon, Libya, Mauritania, Morocco, Palestine, Sudan, Syria, Tunisia, and Yemen) as well as the following other countries: United Arab Emirates, Saudi Arabia, Oman, Somalia, Qatar and Comoros Island.

Important parameters for the selection of a solar cooling technology for a specific country are:

- Electricity cost
- Solar radiation potential
- Climatic conditions

Figure 5: Arab countries map (Source: Solem Consulting - Updated by RCREEE 2015)

The location of the 22 Arab countries clearly shows that the majority of the countries are situated in the Middle East and Northern Africa region (MENA), which means a dry and hot climate. Some exceptions are included such as the Comoros islands, located in a tropical climate, and the northern parts of Tunisia, Algeria and Morocco located in a Mediterranean climate.

Looking at a solar irradiation map (Figure 6), nearly all the Arab countries benefit from very good solar resources with values between 2,000 and 2,500 kWh/m^2.y (horizontal annual sum), as shown in Figure 6. Starting from this, it appears that the solar cooling technologies will have to be applied in dry but very rarely humid climates.

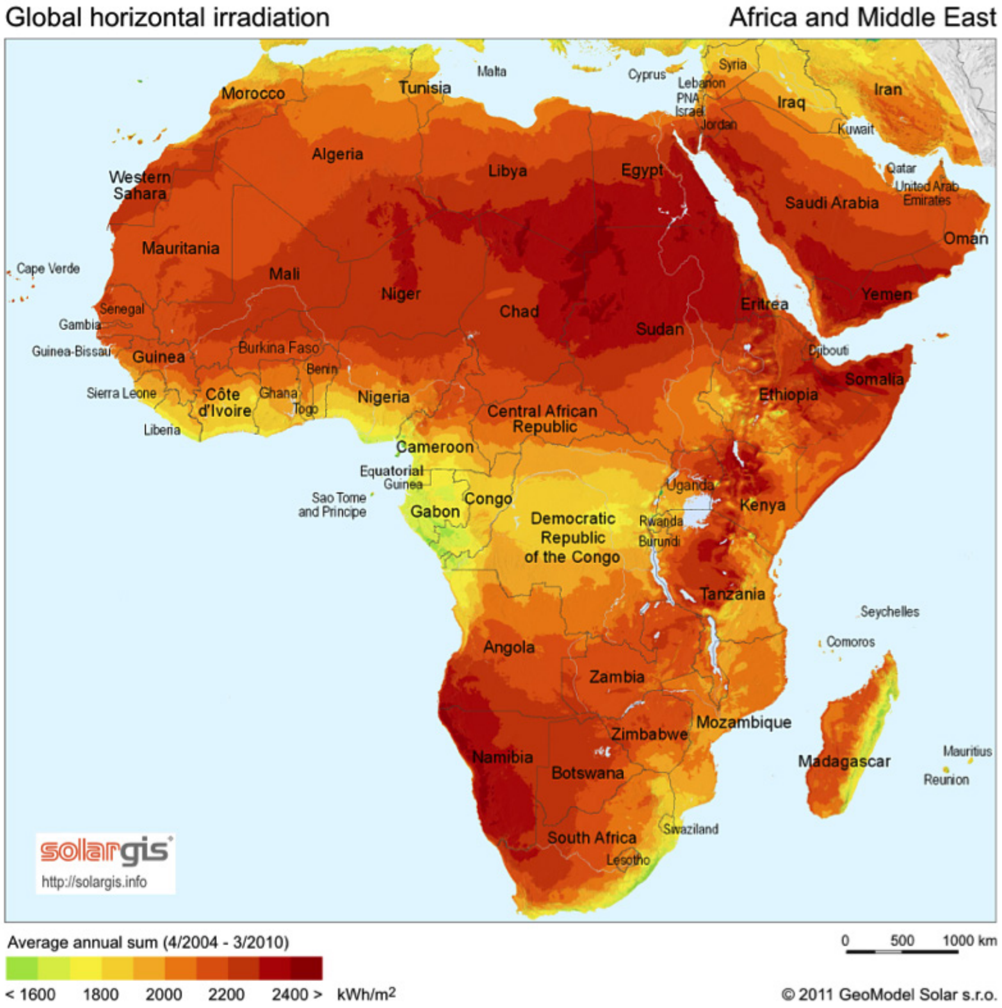
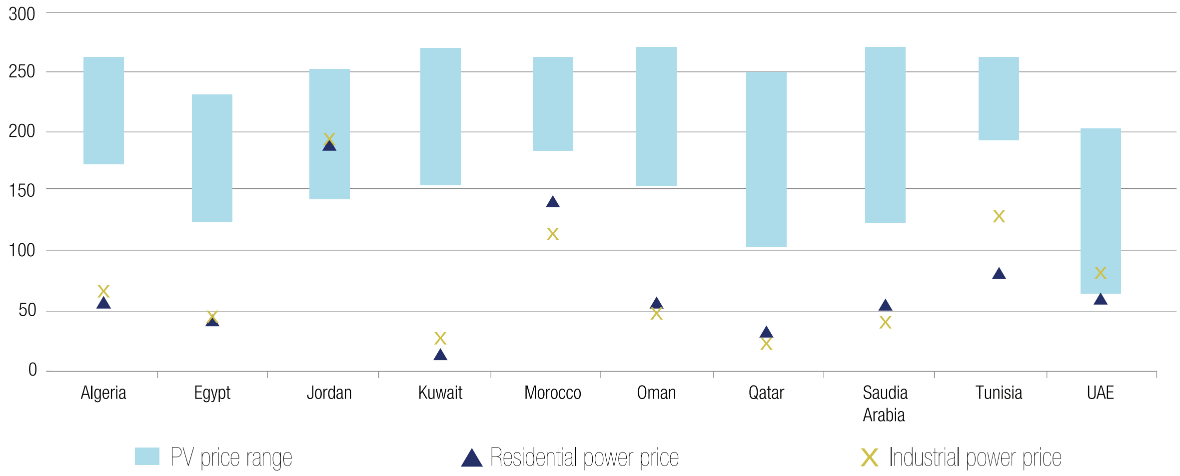


Figure 6: Global horizontal irradiation for Africa and Middle East (Source: solargis.info [10])

For both types of solar cooling systems the electricity price is an important parameter for the economics. Figure 7 shows the electricity retail price of MENA countries as well as the LCOE (Levelized Cost of Energy) of a PV system.



Note: Retail power prices include taxes. PV price range combines quantitative and qualitative assessment

Figure 7: Retail Power Price Level compared to PV LCOE for selected Arab countries (Source: IHS, 2015, [11])

However, the residential power price in the Arab region is historically low and the Figure 8 shows the potential of savings is far bigger for larger applications (tertiary and industrial) where the electricity tariffs are much higher.

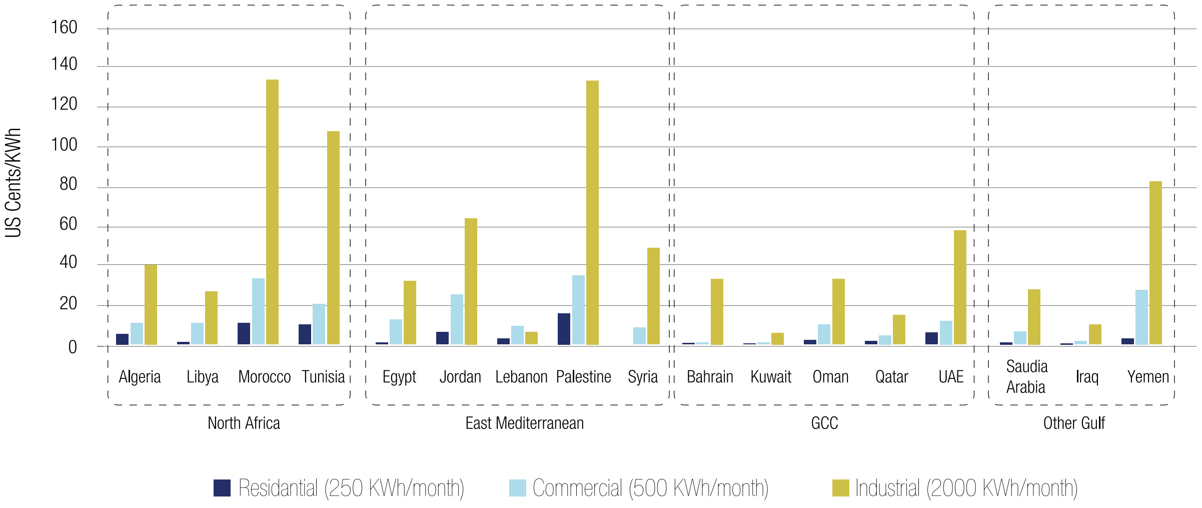
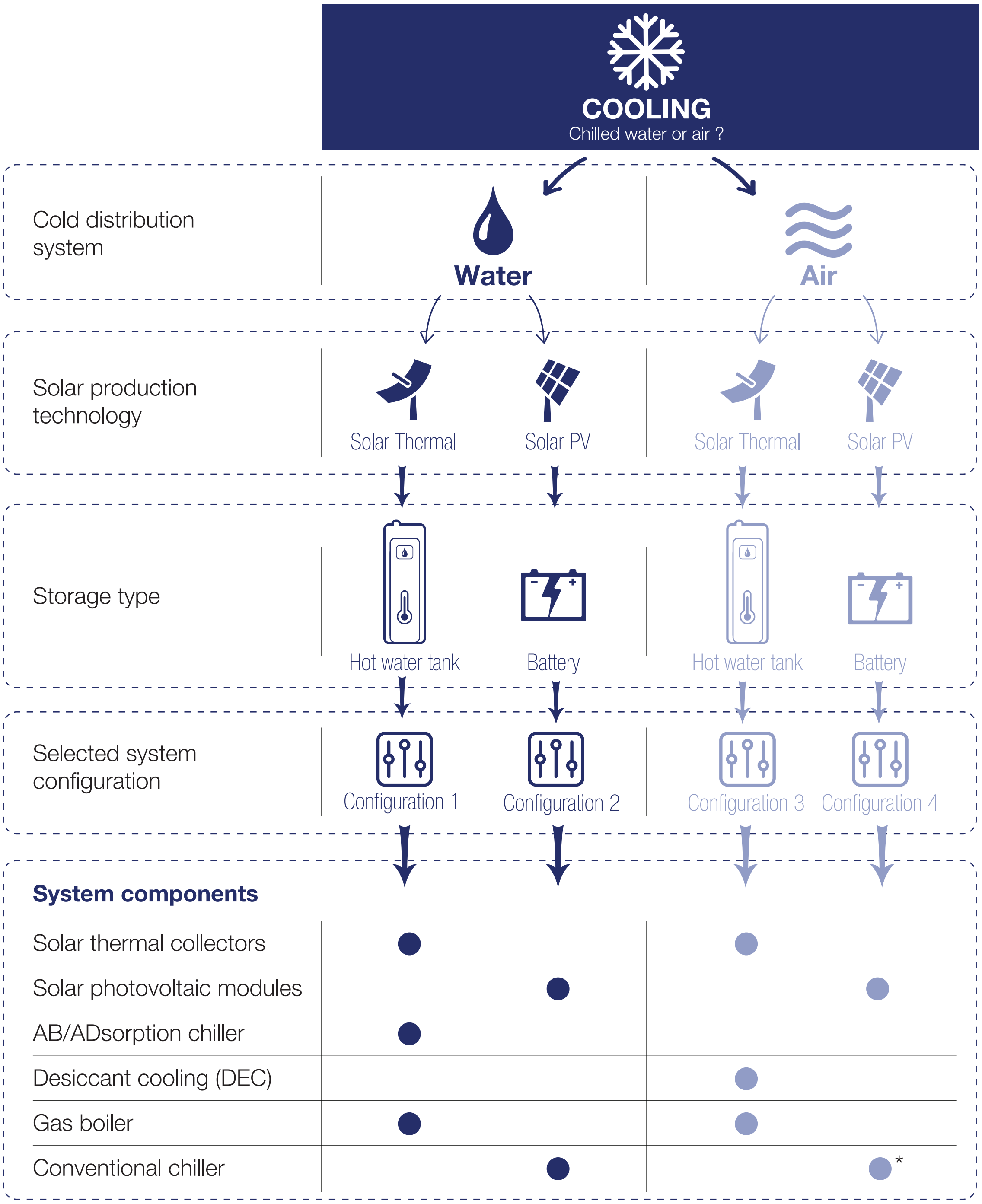


Figure 8: Residential, Commercial, and Industrial Electricity Prices in selected Arab Countries, 2012 (Source: Oxford Institute of Energy, [12])

For larger applications, which are the core of the present study, depending on the type of building and applications, the distribution medium will be potentially chilled water or air. This criterion will mainly depend on the size and type of building, including zones requiring more or less important fresh air ventilation rates.
Another important aspect to be mentioned is the need to use simple-to-maintain systems in the Arab countries where harsh climatic conditions are very often present: dust, wind, extreme temperature variations.

These first orientations permit to present a basic decision scheme (Figure 9), which strongly reduces the number of possible solar cooling technologies in the Arab region.



System components	Configuration 1	Configuration 2	Configuration 3	Configuration 4
Solar thermal collectors	●		●	
Solar photovoltaic modules		●		●
AB/ADsorption chiller	●			
Desiccant cooling (DEC)			●	
Gas boiler	●		●	
Conventional chiller		●		●*

(* with additional air-water heat exchanger air handling unit)

Figure 9: Decision scheme for solar cooling technology selection
(Source: Solem Consulting)

The analysis of Figure 9 shows that there are four main configurations with two heat driven solutions (1 and 3) and two electrically driven solutions (2 and 4).

Configuration 1 is the solar thermal option, using solar thermal collectors, a sorption chiller and a gas boiler included with this option. The latter is required if the targeted building (i) uses just a sorption chiller as the main cooling device or (ii) has hot water needs for domestic or space heating purposes. If an electrical vapour compression chiller is already present in the building as a back up source then the solar thermal cooling system can work without a gas boiler.
Configuration 2 and 4 are the PV cooling options. They differ only in the way the cold is distributed. **Configuration 2** is using a central water chiller and is therefore typically to be used for larger, water-based A/C systems. Configuration 4 is using air to distribute the cold. This can also be realised with a central water chiller and an air-handling unit where cold is transferred from water to air. But **Configuration 4** is here interpreted as the direct-expansion option mentioned on p. 23. There, refrigerant evaporates directly, heated by a passing air stream. Cold is therefore transferred directly to the air, not to water. **Configuration 3** (Desiccant evaporative cooling, DEC) is designed to operate in high humidity climates, which is not the case for almost all the Arab region countries. In addition, this technology is quite complex and not very efficient if the climate is dry. It is therefore excluded from the list of possible system configurations.

The cooling load profile (i.e. the fluctuation of cooling demand over a time period) in the Arab region can vary from constant needs (e.g. Middle East countries during Summer) and mostly daily needs (e.g. Northern African countries outside of Summer). For both regions the solar production, even without using storage capacity, has good coincidence with the momentary cooling load. Thus, storage capacity (thermal one for solar thermal collectors and electrical one for PV panels) can be minimised or even excluded, which is an advantage in terms of reduced upfront investment cost.
This is why the main priority building sectors for the present study are the ones having a predominantly daily load: hotels, office buildings, commercial centres and some specific industry applications. This choice permits to cover applications all over the Arab region and so as to lead to the most competitive solar cooling systems avoiding important costs for storage (either thermal or electrical).
The typology of the targeted buildings mentioned above generally leads to cooling power loads of tens to hundreds or thousands kW_c. Therefore, they are generally including a centralized chilled water circuit connected to a conventional vapour compression chiller in this power range.
Other important criteria to select technologies for Arab region conditions are following:

- the solar cooling technologies will have to be very robust and simple to maintain in harsh hot and arid conditions. Therefore, solar cooling systems need to have been checked and demonstrated in the above mentioned conditions
- as solar cooling technology is having high upfront costs, each produced kWh of cooling needs to be generated with potentially high efficiency.

In the range of cooling power from 100 kW_c to several MW_c and in areas where direct irradiation level is high, the most efficient solar thermal cooling systems are using absorption double effect chillers leading to thermal COP above 1. Solar collector technologies adapted to double-effect absorption chillers are concentrated collectors (Parabolic through or Fresnel).
For PV cooling solutions, the most adapted compression chillers are scroll ones because having the best flexibility to fit with PV source variations in this range of cooling power.
A rational methodology, starting from the different available technologies, leads to the selection of 2 options:

- Double-effect absorption chiller and concentrating collectors
- Vapour compression scroll chiller and PV modules

Main conclusions:

The target buildings in Arab region where solar cooling is accurate are the ones having a predominant daily cooling load. To cover a large spectrum of markets in the Arab region, the solar cooling technologies will have to be very robust and simple to maintain in harsh hot and arid conditions. As solar cooling technology is having high upfront costs, each produced kWh of cooling needs to be used in the best efficiency. That is why the follow up of the study will concentrate on developing the analysis of 2 driving technologies for solar cooling:

- Double-effect absorption chiller and concentrating collectors
- Vapour compression scroll chiller and PV modules

2.2 LCA of selected solar cooling technologies for the Arab region

In order to identify the most suitable technologies for the Arab region, a Life Cycle Assessment (LCA) is conducted in this study. The assessment compares both solar thermal cooling and solar PV Cooling with conventional solutions. The quality of a LCA strongly depends on the chosen specific system configuration as well as the quality of information, e.g. the specific list of materials used. It is beyond the scope of this study to collect all the information required for an extensive comparison.

However, one outcome of the IEA-SHC Task 48 was a very accurate LCA methodology for comparing solar cooling systems ([13]). The methodology is based on the listing of the main components of the chosen system as well as the ones of the reference system. In addition, boundary conditions are considered to show the energy mix from the country in which the solar cooling system is to be used. In the IEA-SHC Task 48, energy and environmental impacts of other components of SHC plants have also been assessed (e.g. solar thermal collectors, gas boiler, pumps, etc.), using data from international LCA databases. Moreover, the energy and environmental impacts of an ammonia/water absorption chiller have been assessed and the database of life cycle inventories for components of solar heating and cooling (SHC) systems, developed within IEA-SHC Task 38, has been updated and completed. Furthermore the LCA database includes solar PV components (photovoltaic panels, inverter, storage, etc.) giving the possibility to perform analysis on conventional systems, which use renewable electricity with or without connection with the grid.

The energy and environmental impact parameters selected to show the performances of the investigated system in terms of LCA are:

- Gobal Energy Requirement (GER, in MJ/kWh),
- Global Warming Potential (GWP in kg CO^2,eq/kWh)

This choice has been made for being most representative indicators to measure the Life Cycle Energy use of solar cooling systems. From the Task 48 work a user-friendly LCA method tool is available. It can be employed to calculate the energy and environmental impacts as well as the payback time indices of different SHC systems. An example of the calculation made for a 12 kW_c solar thermal absorption cooling system in Tunisia is given as follows.

The assumed boundary values for Tunisia are the following for electricity (low voltage level, at grid) :

GER (Global Energy Requirement): 13.35 MJ/kWh

- GWP (Global Warming potential): 0.805 kg CO^2,eq/kWh

For gas, no values could be collected for Tunisia, but a good assumption was to use the values for Natural gas, burned in an atmospheric, non-modulating boiler <100 kW_{th} in Europe:

- GER (Global Energy Requirement): 4.44 MJ/kWh
- GWP (Global Warming potential): 0.265 kg CO^2,eq/kWh

The LCA comparison has been made for two cases:

2.2.1 Case 1: SHC system with cold backup installed in Tunisia, in comparison with a conventional system

This example describes the application of the LCA method tool to carry out a LCA of a SHC system that operates with a cold backup configuration, installed in Tunisia, in comparison with a conventional system. In this example, both the SHC and the conventional (reference) system have an assumed useful lifetime of 25 years.

The SHC system is constituted by the following components:

- Absorption chiller (12 kW_c);
- Evacuated solar collectors (35 m^2);
- Heat storage (2000 l);
- Cooling tower (32 kW_{th});
- Auxiliary gas boiler (10 kW_{th});
- Auxiliary conventional chiller (10 kW_c);
- Pipes (60 m);
- Pump (80 Wel);
- Pump (250 Wel).

The system uses a water/ammonia solution (15 kg of ammonia and 10 kg of water). During annual operation, the SHC system consumes 1,117 kWhel/year of electricity and 414 kWhth/year of natural gas. The conventional system is constituted by the following components:

- Vapour-compression chiller (10 kW_c)
- Gas boiler (10 kW_{th})

During annual operation it consumes 1,995 kWhel/year of electricity and 2,882 kWhth/year of natural gas. Using the LCA Tool from IEA SHC Task 48, the results of this comparison are shown as follows. A comparison of the GER and the GWP of the SHC system with those of the conventional system is shown in Figure 10 and Figure 11.

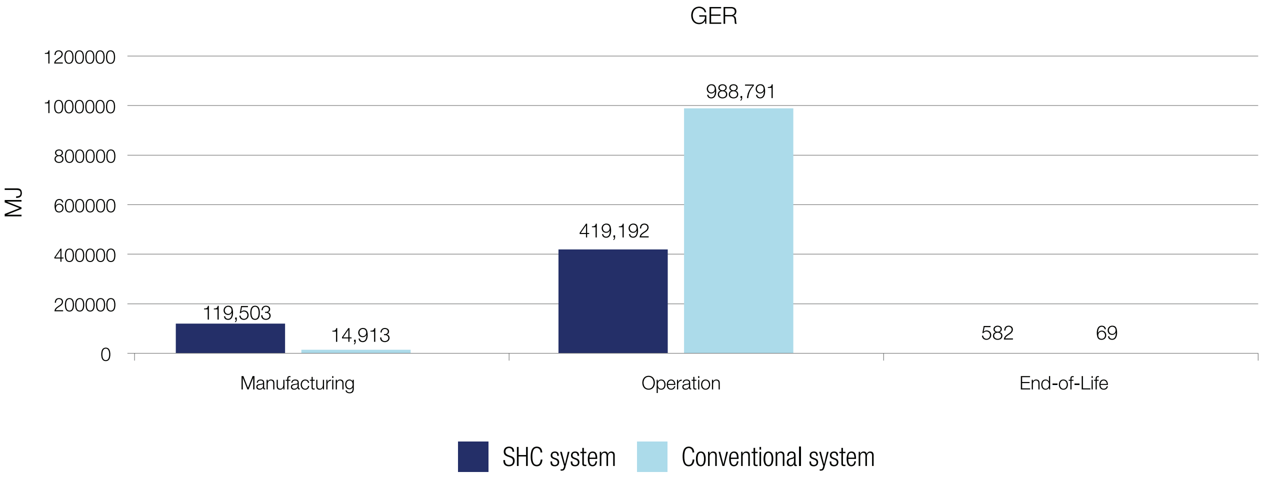


Figure 10: Global Energy Requirement (GER) comparison between SHC and conventional system

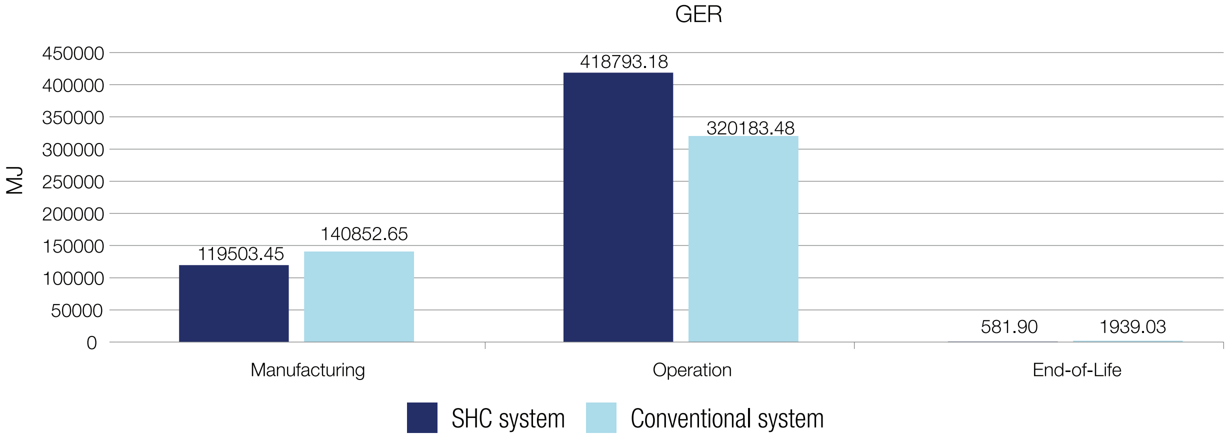


Figure 11: Global Warming Potential (GWP) comparison between SHC and conventional system

The comparison shows that the total lifetime numbers add up to the following:

Total life time GER:	SHC: 539,277 MJ	CONV: 1,003,773 MJ	(+86%)
Total life time GWP:	SHC: 10,497 kgCO^2,eq	CONV: 21,194 kgCO^2,eq	(+93%)

It can be concluded that the chosen SHC system has lower energy consumption and lower emissions than the conventional system. In detail, the values of GER and GWP for the conventional system are approx. 90% higher than for the SHC system. In particular, the higher impacts caused by the SHC system during the manufacturing and end-of-life steps are balanced by the energy savings and avoided emissions during the operation step. Thus, the results of the comparison show the advantages of such a SHC system in substitution of a conventional one.

When calculating energy and emission payback indices, Figure 12 shows interesting results. The Energy and GWP payback time periods of the SHC system (in order to harvest as much energy as is being used in the process of manufacturing) are approx. 4.6 years and 8.8 years, respectively. This highlights that the additional impacts caused for the manufacturing and end-of-life steps of the SHC system are equalized by the generated yearly energy savings and avoided GWP impact in a time period under 9 years. The value of Energy Return Ratio is about 4.7. This means that the energy saved during the useful life of the SHC system overcomes the global energy consumption due to its manufacture and end-of-life of approx. five times.

Energy Payback Time=(GER$_{SHC\text{-}system}$-GER$_{Conventional\text{-}system}$)/E$_{year}$

Energy Payback Time is defined as the time during which the SHC system must work to harvest as much primary energy as it requires for its manufacturing and end-of-life. The harvested energy is considered as net of the energy expenditure for the system use.

GER $_{SHC\text{-}system}$	=	120,085	MJ
GER $_{Conventional\text{-}system}$	=	14,982	MJ
E$_{year}$	=	22,784	MJ/year
Energy Payback Time	=	4.6	year

GWP Payback Time=(GWP$_{SHC\text{-}system}$-GWP$_{Conventional\text{-}system}$)/GWP$_{year}$

GWP Payback Time is defined as the time during which the avoided GWP impact due to the use of the SHC system is equal to GWP impact caused during its manufacturing and end-of-life.

GWP$_{SHC\text{-}system}$	=	7,733	kgCO$_{2eq}$
GWP$_{Conventional\text{-}system}$	=	1,954	kgCO$_{2eq}$
GWP$_{year}$	=	659	kgCO$_{2eq}$/year
GWP Payback Time	=	8.8	year

Energy Return Ratio=E$_{overall}$/GER$_{SHC\text{-}system}$

Energy Return Ratio represents how many times the energy saving overcomes the global energy consumption due to the SHC system.

GER$_{SHC\text{-}system}$	=	120,085	MJ
E$_{overall}$	=	569,599	MJ
Energy Return Ratio	=	4.7	

Figure 12: Payback time comparison between SHC and conventional system
(Source: Task 48 LCA tool)

2.2.2 Case 2 : SHC system with a cold backup installed in Tunisia, in comparison with a PV cooling system including batteries and grid connection

This example describes the application of the LCA method tool to carry out a LCA of a SHC system that operates with a cold backup configuration, installed in Tunisia, in comparison with a PV cooling system including both batteries and grid connection. Again, the assumed lifetime for both systems is 25 years, except where mentioned otherwise. The SHC system is the same as in Chapter 2.2.1. The PV cooling system is constituted by the following components:

- conventional chiller (10 kWc)
- gas boiler (10 kW)
- 33 m^2 of multi-Si photovoltaic panels
- inverter (2,500 W, lifetime 12.5 years)
- lithium-ion-manganate battery (50 kg, lifetime 8.3 years)

During annual operation the system consumes 2,882 kWhth/year of natural gas. The electricity consumed by the system is produced 100% by the photovoltaic system. During the life cycle of the system two inverters and three batteries have to be installed.
The results of the comparison are shown in Figure 13 and Figure 14.

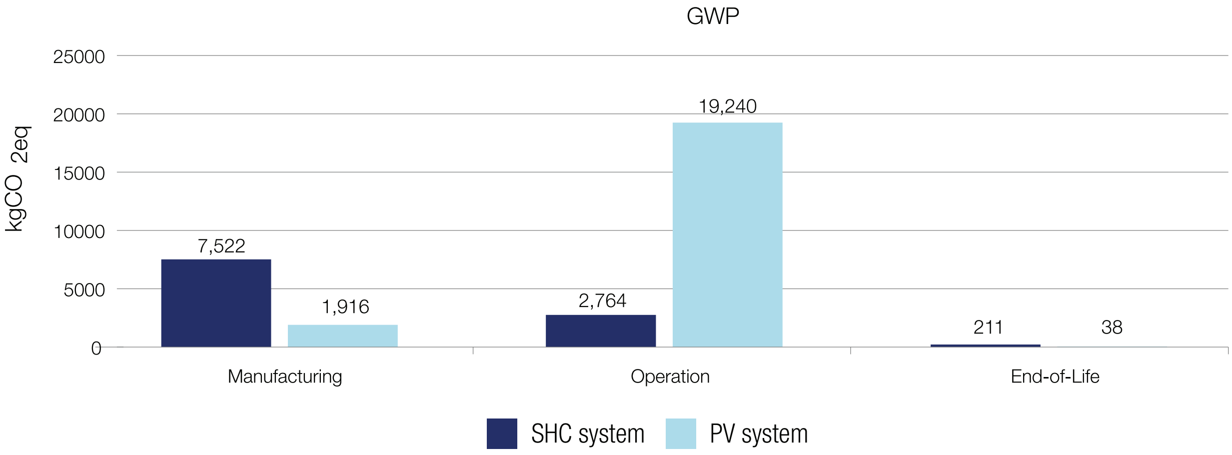


Figure 13: Global Energy Requirement (GER) comparison between SHC and PV system

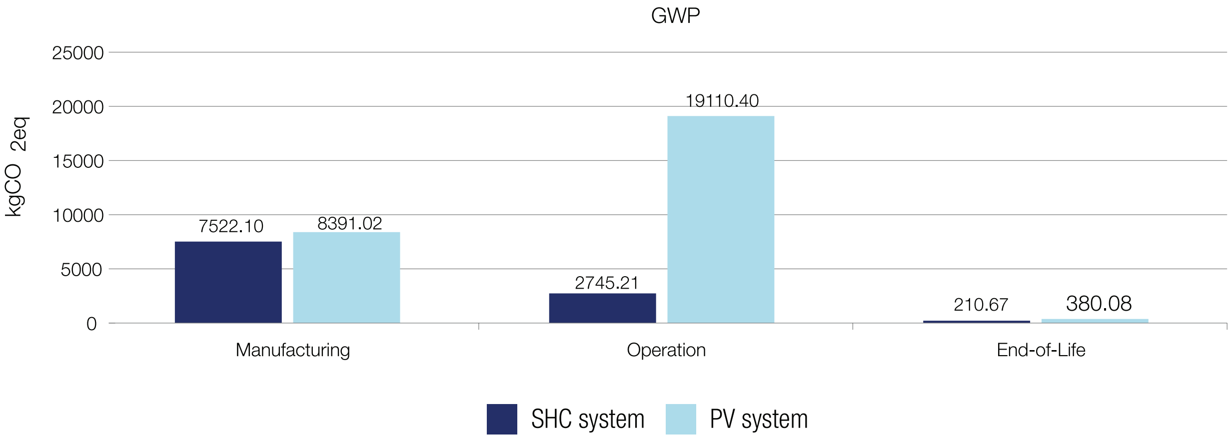


Figure 14: Global Warming Potential (GWP) comparison between SHC and PV system

The comparison of GER and GWP shown in Figure 13 and Figure 14 indicates that the SHC system has the lowest global warming potential. However, the PV system shows lower global energy requirement. The total lifetime numbers add up to the following:

Total life time GER:	SHC: 539,277 MJ	PV: 462,974 MJ	(-14%)
Total life time GWP:	SHC: 10,497 $kgCO^2$,eq	PV: 27,881 $kgCO^2$,eq	(+166%)

The contribution of the battery system has been investigated individually. Figure 13 and Figure 14 show the contribution of the battery to the total impacts due to the manufacturing and end-of-life. In detail these are:

- during the manufacturing step the battery contributes approx. 12% on GER and approx. 27% on the total GWP;
- during the end-of-life step the battery is the main contributor to GER (approx. 97.5%) and is responsible for approx. 64% of the impact on GWP.

An analysis of the “payback indices” in Figure 15 shows that the following items, related to the use of the SHC system in substitution with the PV system, have negative values:

- net yearly primary energy saving;
- net yearly avoided GWP;
- net primary energy saving during the overall life cycle of the SHC system.

This means that during operation the impacts of the SHC system are higher than of the PV one, which uses electricity produced by renewable energy sources. Even if PV has worse performances during operation than the solar thermal solution, the total energy and environmental impacts of the PV system are lower than the one of the SHC system. In this case, the calculation of the payback time indices cannot be carried out.

Energy Payback Time=$(GER_{SHC\text{-}system}-GER_{Conventional\text{-}system})/E_{year}$

Energy Payback Time is defined as the time during which the SHC system must work to harvest as much primary energy as it requires for its manufacturing and end-of-life. The harvested energy is considered as net of the energy expenditure for the system use.

$GER_{SHC\text{-}system}$	=	120,085	MJ
$GER_{Conventional\text{-}system}$	=	142,792	MJ
E_{year}	=	-3,944	MJ/year
Energy Payback Time	=	5.8	year

GWP Payback Time=$(GWP_{SHC\text{-}system}-GWP_{Conventional\text{-}system})/GWP_{year}$

GWP Payback Time is defined as the time during which the avoided GWP impact due to the use of the SHC system is equal to GWP impact caused during its manufacturing and end-of-life.

$GWP_{SHC\text{-}system}$	=	7,733	$kgCO_{2eq}$
$GWP_{Conventional\text{-}system}$	=	8,771	$kgCO_{2eq}$
GWP_{year}	=	655	$kgCO_{2eq}$/year
GWP Payback Time	=	-1.6	year

Energy Return Ratio=$E_{overall}/GER_{SHC\text{-}system}$

Energy Return Ratio represents how many times the energy saving overcomes the global energy consumption due to the SHC system.

$GER_{SHC\text{-}system}$	=	120,085	MJ
$E_{overall}$	=	-98,610	MJ
Energy Return Ratio	=	-0.8	

Figure 15: Payback time comparison between SHC and PV system. Source: Task 48 LCA tool.

Main conclusions on life cycle assessment (LCA) of solar cooling systems:

The case studies described above show a comparison of SHC systems with conventional and PV cooling ones. The results of the case studies provide a comprehensive investigation of the energy and environmental performance of solar assisted cooling systems during their life cycle.

As a result, for the small cooling capacity range for residential applications in Tunisia, the LCA clearly shows a net advantage for solar cooling and heating solutions in comparison with conventional ones but with an advantage for the PV approach in comparison with the solar thermal one.

Note: An equivalent LCA could not be conducted as part of this study for larger system sizes because of the lack of detailed information on large chillers.

2.3 Identified solar cooling technologies for the Arab region

In Chapter 2.1, the following requirements on suitable solar cooling technologies for the Arab region have been identified:

- the target buildings in Arab region where solar cooling is accurate are the ones having a predominant daily cooling load
- to cover a large spectrum of markets in the Arab region, the solar cooling technologies will have to be very robust and simple to maintain in harsh hot and arid conditions
- as solar cooling technology is having high upfront costs, each produced kWh of cooling needs to be generated with potentially high efficiency
- two technologies are emerging to be the most suitable ones for the Arab region:
  - Double-effect absorption chiller and concentrating collectors
  - Vapour compression scroll chiller and PV modules

This chapter is now aimed at identifying the solar cooling technologies adapted for the Arab region and especially at quantifying which technology is more interesting than another one. As the Arab region is made of 22 countries, it is important to perform this analysis by differentiating these countries according to their boundary conditions (solar radiation, energy cost, climate).

The requirements identified in Chapter 2.1 have led to the following expert choices:

Target buildings:

Buildings with a potentially constant cooling load during the day will be used. These are typically commercial and industrial buildings. Residential sized buildings have been excluded, since their cooling load varies significantly during the day. Two building types/sizes have been chosen:

a) **Medium:** Average commercial building of 500 to 1,000 m^2 air-conditioned area (depending on the location in Arab region). Cooling capacity approx. 100 kW_c

b) **Large:** A group of buildings (using a distributed cooling network) or a large building, air-conditioned area of 5,000 to 10,000 m^2. Cooling capacity approx. 1 MW_c.

For the large building type, only the following countries have been selected: Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and UAE. Indeed, this selection of countries is corresponding to cities where there are both numerous large air-conditioned buildings and significant zones close to these buildings or on the building roofs where important solar collector areas can be implemented.

The assumptions for the calculations are:

- The solar cooling production is fully in coincidence with the building load. This minimises the need for storage capacity.
- The installed cooling capacity is undersized. This allows the majority of the solar cooling production to be used in the building.
- The targeted buildings are using solar energy only for cooling purposes, not for space or domestic hot water heating.

Highly efficient system configuration:
In order to use the solar energy with maximum efficiency, the following two configurations have been chosen:

- Solar thermal: Double-effect absorption chiller with a small hot water tank and hybrid cooling tower
- Solar PV: scroll vapour compression chiller with battery storage and wet cooling tower
- Reference: scroll vapour compression chiller with wet cooling tower

Before the simulation has been undertaken a detailed analysis of the boundary conditions in the countries of the Arab Region has been conducted, using inputs from different studies and from RCREEE studies. The sources of all of these data can be found in Appendix 2. Table 2 shows the results of this investigation including costs in USD and energy data for different countries.

Table 2: Selected Arab countries indicators (electricity and water costs for commercial applications)

	Global Horizontal Irradiation	Direct normal Irradiation	PV yield, (°20 tilt ; South)	Electricity cost for commercial	% of subsidy on electricity tariff for commercial	Water cost
	kWh/m^2.y	kWh/m^2.y	(kWh/ kWp.y)	(cUSD/ kWh)		(USD/m^3)
Algeria	1,970	2,700	1,600	4.2	78%	0.5
Bahrain	2,160	2,050	1,900	0.8	96%	8
Egypt	2,450	2,800	1,730	9.9	49%	0.4
Iraq	2,050	2,000	1,800	1.1	94%	0.05
Jordan	2,320	2,700	1,800	17	12%	1.47
Kuwait	1,900	2,100	1,900	0.7	96%	0.75
Lebanon	1,920	2,000	1,700	10.4	46%	1
Libya	1,940	2,700	1,700	5.5	71%	0.05
Morocco	2,000	2,600	1,700	16.1	16%	1.5
Oman	2,050	2,200	1,900	5.2	73%	2
Palestine	1,920	2,000	1,800	19.2	0%	1.2
Qatar	2,140	2,200	1,900	2.5	87%	1.4
Saudi Arabia	2,130	2,500	1,930	3.2	83%	1
Sudan	2,130	2,500	1,950	7.7	60%	0.3
Syria	2,360	2,200	1,800	5.1	74%	0.3
Tunisia	1,980	2,400	1,600	16	17%	0.6
United Arab Emirates	2,120	2,200	1,900	8	58%	0.6
Yemen	2,250	2,200	1,900	14	27%	0.3

It is to be noted that Comoros Islands as well as Djibouti, Mauritania and Somalia are missing in this table even though they are part of the Arab league. This is mainly because data for solar resources as well as economic indicators (energy prices) in these four countries is only scarcely available. Table 2 shows an interesting indicator: the percentage of implied subsidy on the national tariff of electricity (Source: RCREEE, based on data from national energy utilities).

The chosen methodology is going to compare the different cooling systems for each country on the basis of a Net Present Cost approach (NPC) and Levelized Cost of Cooling Energy (LCCE).

2.3.1 100 kW$_c$ segment

The comparative analysis is performed for each of the 18 countries using direct normal irradiation (DNI, 3rd column in Table 2) as the main input for solar thermal cooling production and the PV yield data (4th column in Table 2) as the main input for the solar PV cooling production. In total, 108 results for Net Present Cost and Levelised Cost of Cooling Energy (LCCE) have been obtained (Figure 16 and Figure 17, respectively). For each Arab country, these two indicators have been calculated for the solar thermal system, the solar PV and the reference vapour-compression system. The system configurations, cost figures and assumptions used for calculating the investment and O&M costs of the three technologies can be found in Appendix 3.

Figure 16 shows the NPC for all countries. It can be observed that the NPC of the solar cooling systems (either solar thermally driven ones or PV driven ones) are in the range of 350,000 USD to 500,000 USD. The NPC for PV systems are nearly always lower than for solar thermal ones (except in Algeria) but in several countries such as Libya, Egypt, the NPC values are very close. The NPC of the reference compression systems are much more varying because they are highly depending on the running costs, especially of course the electricity tariffs.

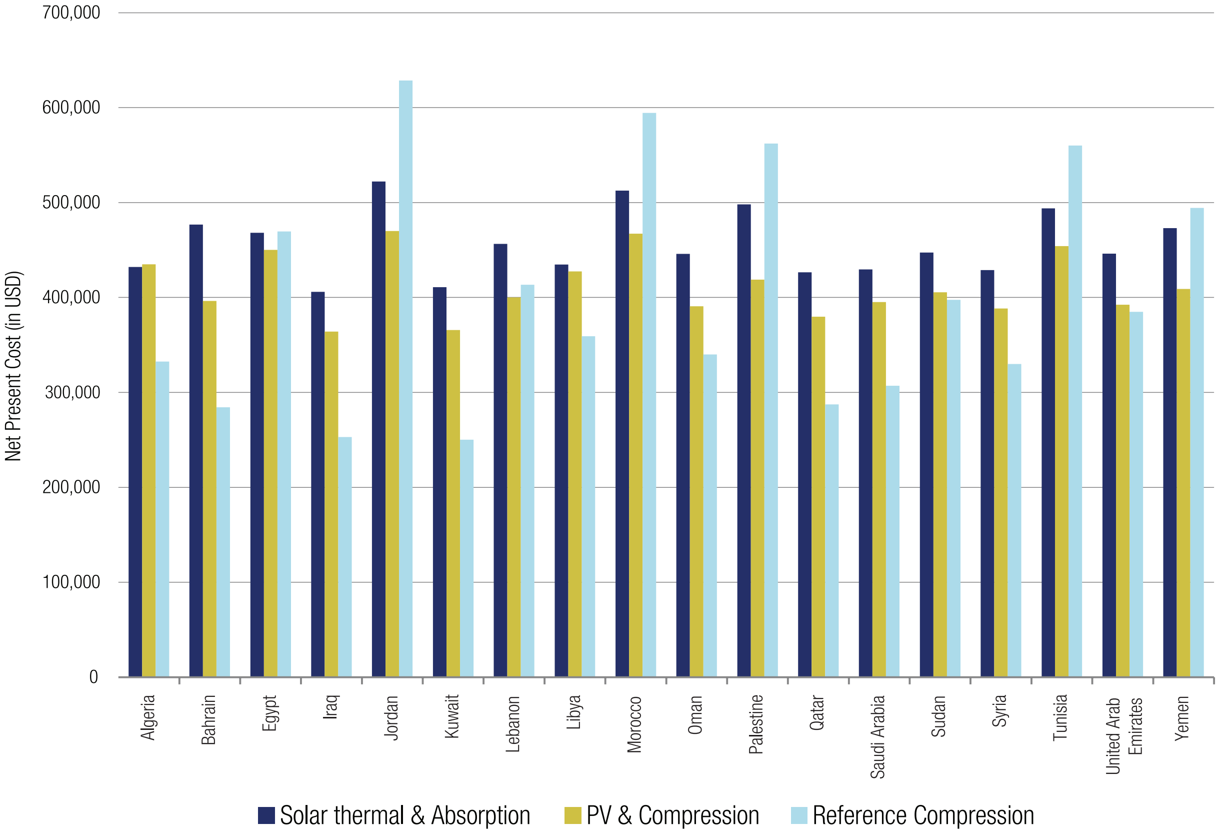


Figure 16: Net Present Cost (20 years) for different configurations and countries

Figure 17 shows the LCCE. It can be seen that in six countries out of 18 (countries marked with orange circles), the LCCE over 20 years is lower for solar cooling (both solar thermal and PV) than for the reference case. In all countries, the solar PV solution has lower LCCE than the solar thermal one.

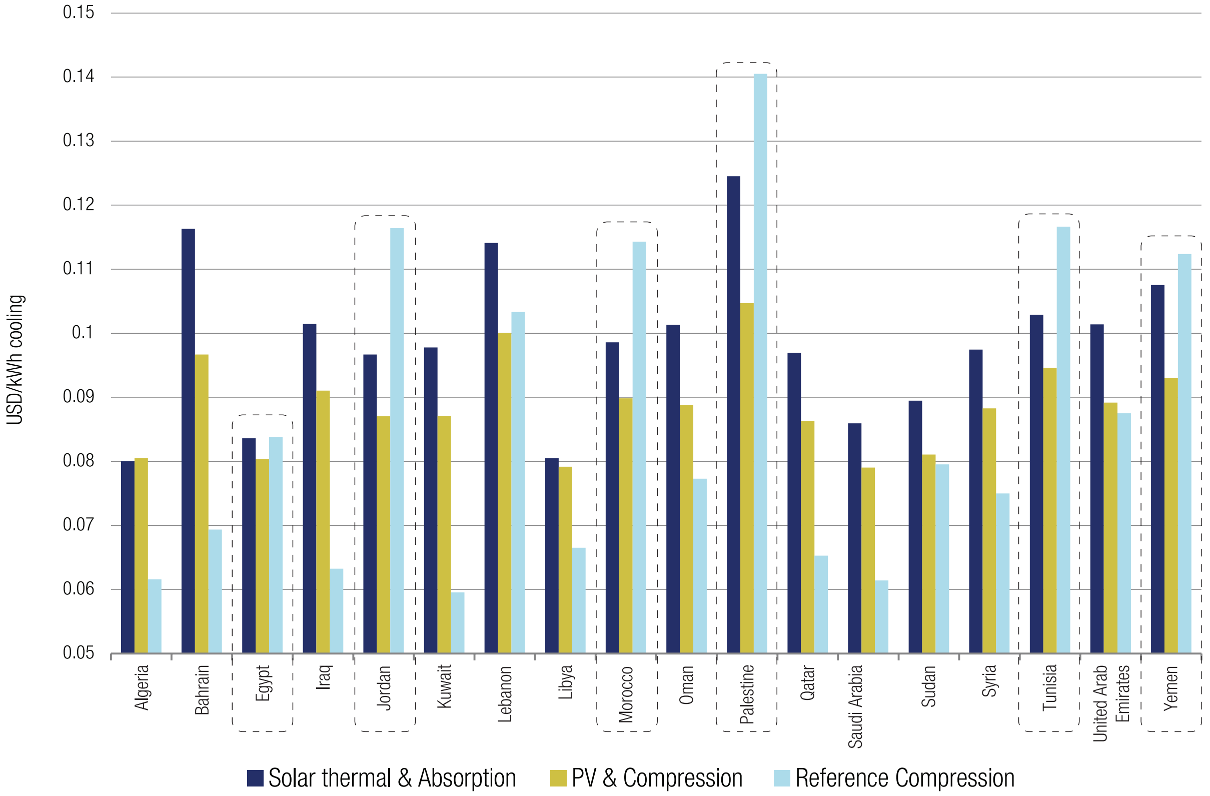


Figure 17: Levelized Cost of Cooling Energy (LCCE) for different configurations and countries.

Even if this approach shows very positive LCCE results for six countries, there are still 12 countries where solar cooling is not competitive yet. If compared with the level of implied subsidies shown in Table 2, the list of the 12 countries becomes evident. Subsidized low cost of electricity makes the solar cooling competitiveness nearly impossible. In these countries, the implied subsidies on electricity are more than 50% (generally from 60 to 90%).

An idea to compensate this implied subsidy could be an equivalent financial subsidy on the upfront cost of the solar cooling technologies. For example, if a 50% grant on the capital cost is used to increase the attractiveness of the solar cooling systems in the 12 specific countries the situation strongly changes. Figure 18 shows the results using a 50% upfront grant. It can be seen that the LCCE is then always lower over 20 years using solar cooling than with a conventional reference system in the countries investigated.

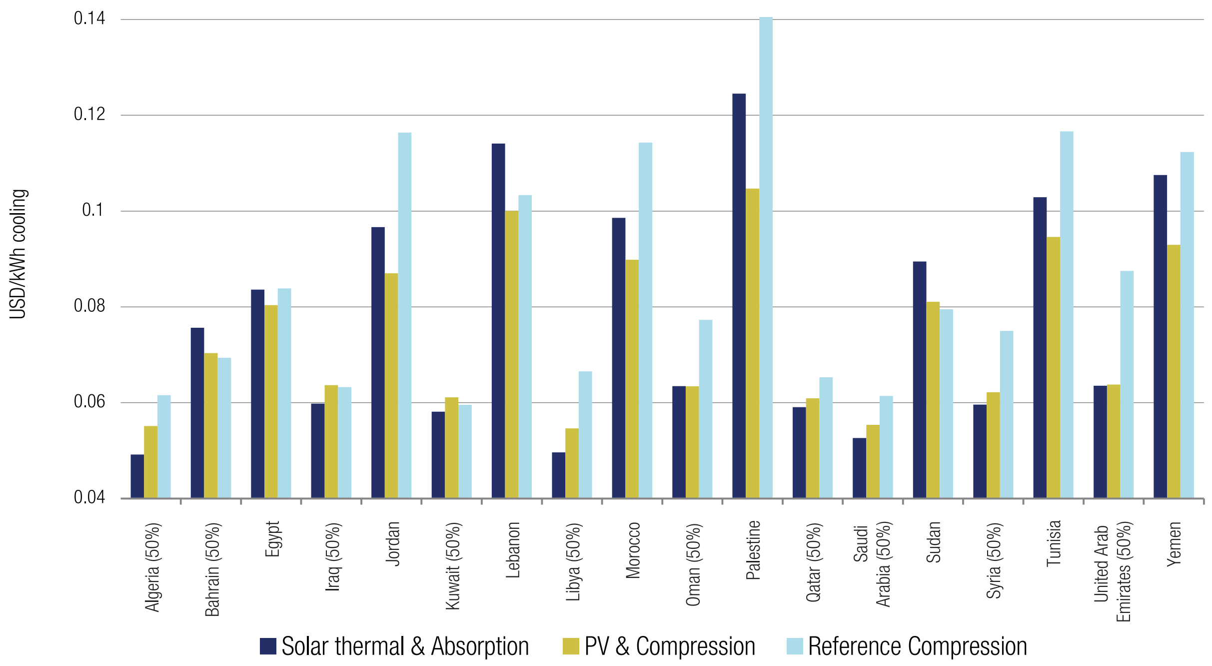


Figure 18: Levelized Cost of Cooling Energy for different configurations and countries (including a 50% subsidy on investment cost for 12 countries)

The ratio of the total subsidy amount delivered to the project and the number of kWh of cooling energy produced over the 20 years of production gives an indication on the performance of a solar cooling system. Figure 19 shows the results for the 100 kW_c segment.

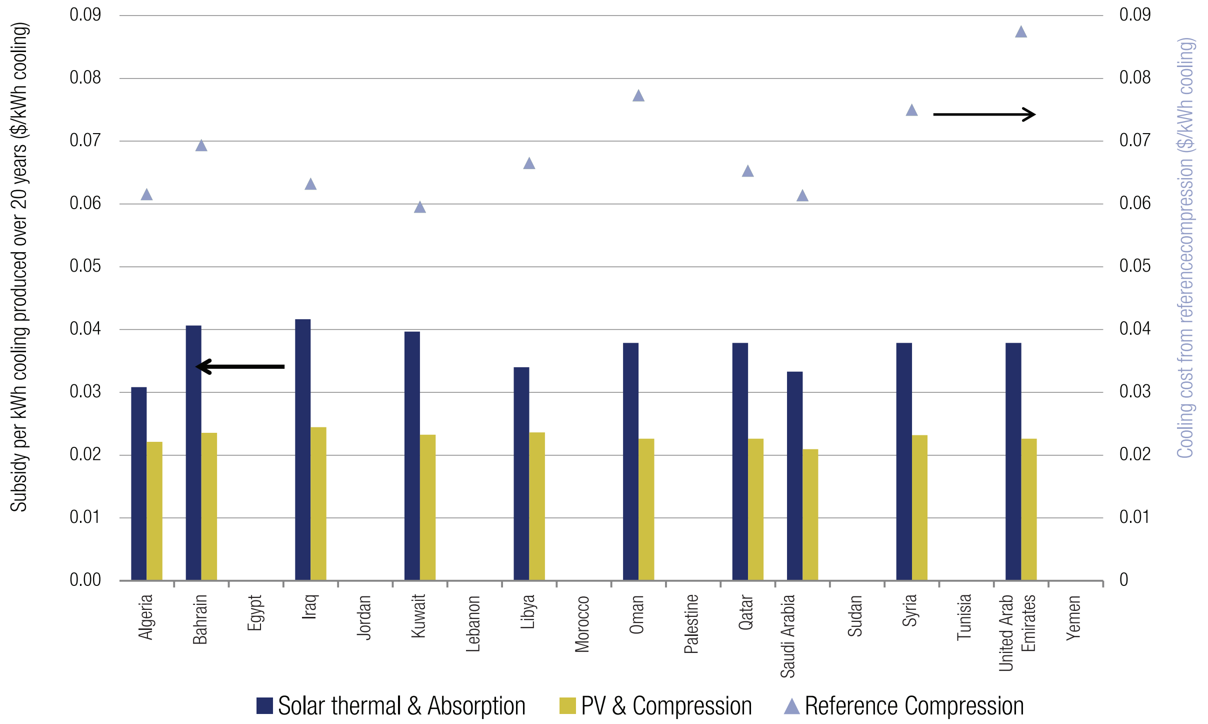


Figure 19: Level of subsidy per lifetime cooling energy (20 years) and reference cooling cost for 12 countries with high subsidies on electricity cost
(see. Table 2)

Figure 19 shows that the subsidy for each kWh of cooling energy is approx. half of the reference cost. For PV cooling (in red) the level of subsidies is approx. 0.02 USD/kWh whereas the cooling cost of the reference system (in green) is between 0.06 and 0.09 USD/kWh. For solar thermal cooling (in blue) the level of subsidies is between 0.03 and 0.04 USD/kWh.

The situation in the 12 targeted countries with a high subsidy of electricity price could thus be improved towards solar cooling with a 50% upfront subsidy on investment cost of the system.

2.3.2 1 MW$_c$ segment

For the 1 MW$_c$ range the system cost changes significantly. The boundary conditions for the countries change as well, with different electricity and water costs (industrial tariff instead of commercial one). This boundary data is shown in Table 3, including only the six countries where large scale systems are easily feasible and corresponds to a significant number of corresponding buildings.

Table 3: Selected Arab countries indicators for the 1 MW$_c$ case
(electricity and water costs for commercial applications)

	Irradiation horizontal kWh/m².y	Irradiation Direct normal kWh/m².y	PV yield (°20 tilt ; South) (kWh/ kWp.y)	Electricity cost for commercial (cUSD/ kWh)	% of subsidy on electricity tariff for commercial	Water cost (USD/m³)
Bahrain	2,160	2,050	1,900	3.8	96%	10
Kuwait	1,900	2,100	1,900	0.4	96%	0.75
Oman	2,050	2,200	1,900	4.2	73%	2
Qatar	2,140	2,200	1,900	1.9	87%	1.2
Saudi Arabia	2,130	2,500	1,930	4.1	83%	1.6
United Arab Emirates	2,120	2,200	1,900	10.8	58%	0.6

With the same methodology as for the 100 kW_c segment, NPC and Levelized Cost of Cooling (LCCE) are calculated for these six countries. The NPC order of magnitude for the 1 MW_c projects is now in the range of millions USD and the average nominal price per kW_c cooling capacity for the solar thermal solution is approx. 1,350 USD.
Figure 20 shows the NPC. Different interesting aspects can be noted:

- In the UAE, solar thermal and solar PV cooling are already more economical than the reference system over 20 years.
- In the other countries, and especially in Kuwait, Qatar and Saudi Arabia, solar thermal and solar PV cooling solutions are very close to each other in terms of NPC

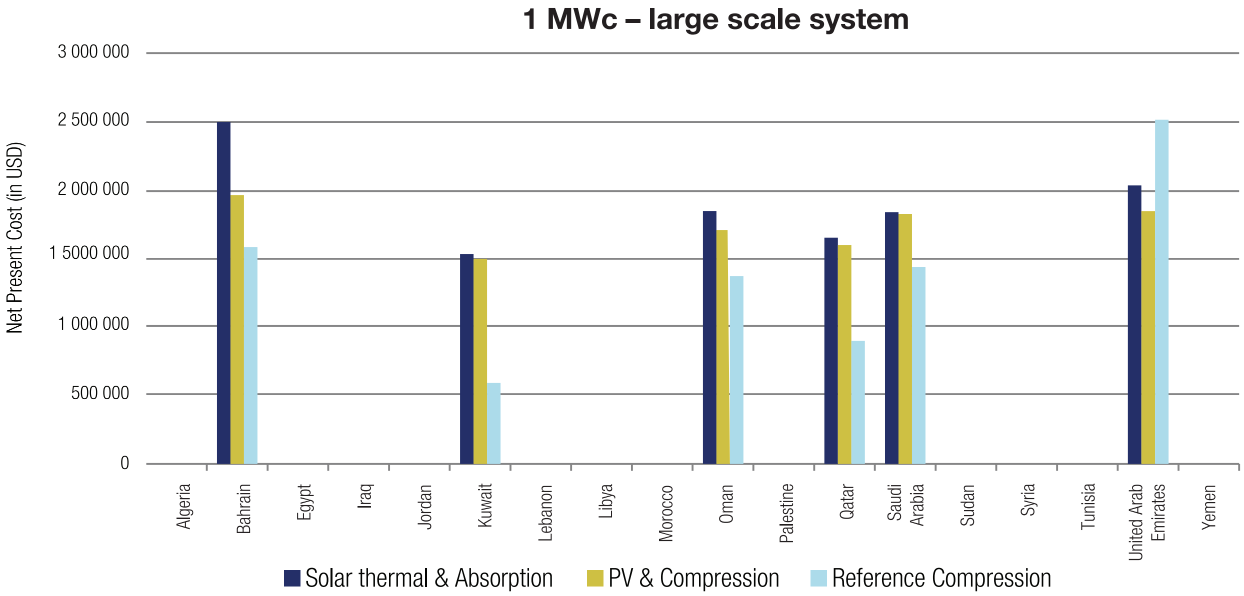


Figure 20: 1 MW$_c$ - Net Present Cost (20 years) for different configurations and countries

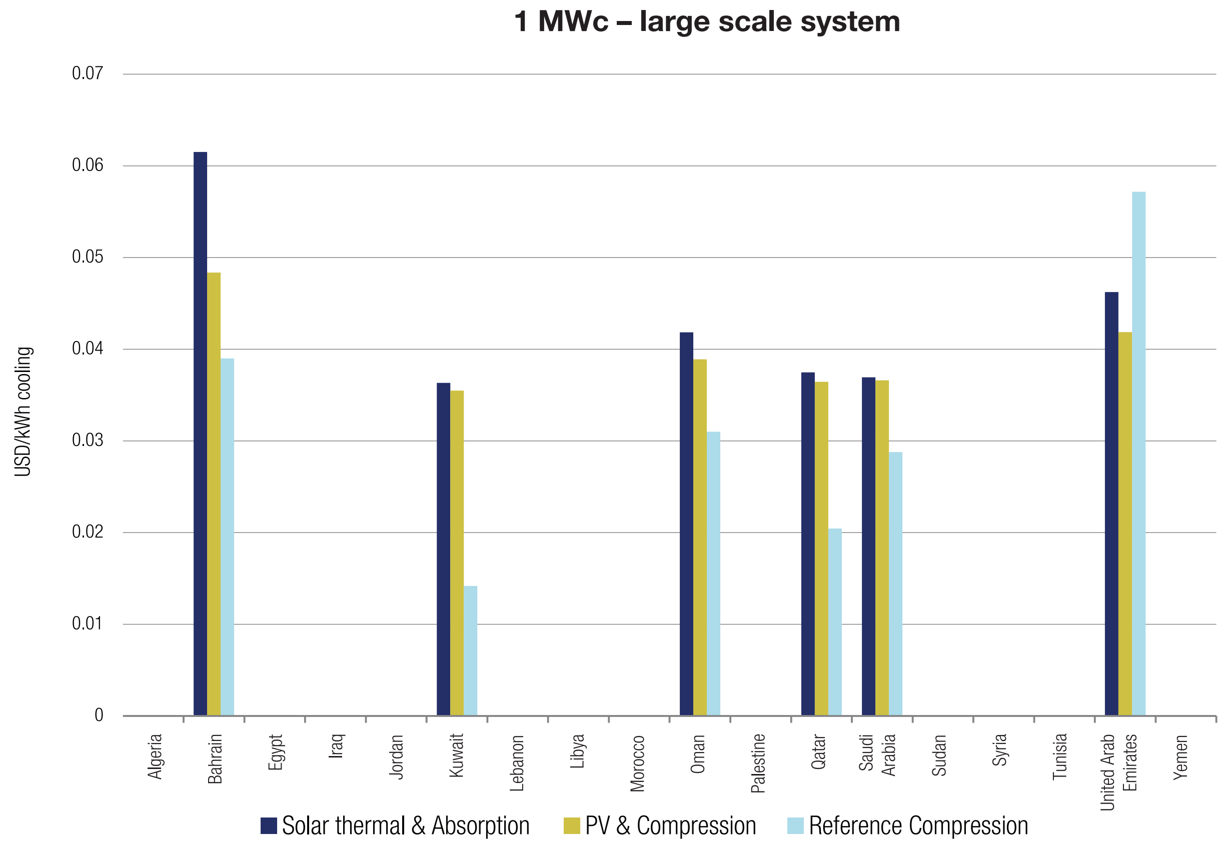


Figure 21: 1 MW$_c$ - Levelized cost of cooling energy for different configurations and countries

Figure 21 shows as well that the LCCE drops to 0.03 to 0.04 USD for the two solar solutions, compared to 0.08 – 0.12 USD/kWh for the 100 kW$_c$ system. If the principle of 50% upfront subsidy on investment cost is also applied to these six countries, the results of Figure 22 can be found.
With a 50% subsidy, solar cooling (both PV and thermal) is cheaper than the reference solution in three countries (Oman, Saudi Arabia and UAE). Under these subsidised conditions the difference between solar thermal cooling and solar PV cooling cost is really small.

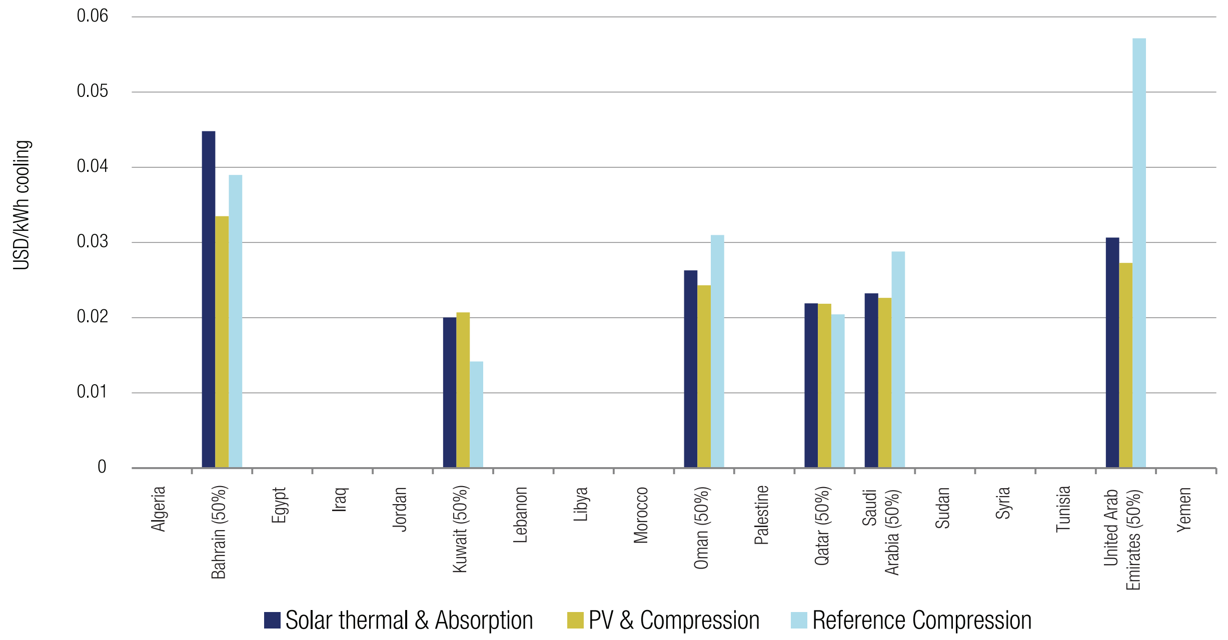


Figure 22: Levelized cost of cooling for different configurations (including subsidies for the specific 6 countries)

It is therefore of interest to take into account some other parameters for the decision between the two. One possible parameter is the size of the solar field, which will be limited by either roof or ground surface. As an example, in Saudi Arabia, the PV field would be approx. 4,700m² whereas solar thermal field would be only 2,460 m². The advantage for saving space is clearly in favour of the solar thermal cooling solution. Even if there is important available space close to some targeted buildings in the Middle East region, this area could be better used for implementing other buildings or city infrastructures (e.g. roads, etc..) Therefore, for the six above mentioned countries, the 1 MW_c segment must be clearly addressed with the solar thermal cooling technology whereas for the 100 kW_c segment, for these countries, the PV cooling technology must be used.

2.4 Expected cost reduction for the Arab region

As it has been seen in the previous Chapter 2.3, solar cooling is already competitive on several markets of the Arab region without subsidies but this is not systematic and will strongly depend on different factors: boundary conditions (energy and water tariffs) as well as the size of the system and the technology used.

Nevertheless, the solar cooling world market is rather small as shown in Figure 3, especially in comparison with the conventional air conditioning one (in 2014 a total number of A/C units of 100 millions units was sold compared to 200-300 solar cooling units). The best-selling solar thermal chiller/ system manufacturer currently have a sales volume of several tens of units per year. Due to such small numbers of manufacturing, a large cost reduction potential can be excepted once manufacturing increases to larger numbers. This cost reduction potential is very important and can be estimated to -15 to -30% cost reduction for the entire system cost, if the annual market volume for these actors would be increased by a factor of 10. The economy of scales is already a very important cost driver when comparing system sizes:

- In the previous calculations, the investment cost for solar thermal cooling has been determined at 3,300 USD/kW_c for a 100 kW_c cooling system. For a 1 MW_c cooling system the cost was found at 1,300 USD/kW_c. This is a reduction of -61 %.
- For the PV & compression system, the investment cost has been determined at 2,100 USD/kW_c for a 100 kW_c cooling system. For the 1 MW_c cooling system cost was found at 1,180 USD/kW_c. This is a reduction of -44%.

Upscaling to larger system capacities already shows an effect at current cost. Changing from a 100 kW_c to a 1 MW_c system leads to a cost reduction per unit of cold production of approx. 50% on average. However, it has to be noted that large scale projects are not possible in each Arab country, since they require specific large building or district cooling networks.
Another cost reduction potential to be expected is the packaging: solar cooling is far from being standardized and packaged, as it is the case for conventional air conditioners. The solar thermal cooling systems are made of numerous components, which are sourced in low volume from manufacturers. Even if the concept of solar cooling kits has become predominant in the sector for a power range below 30 kW_c, the level of packaging is still low and there is still an important engineering effort to lead to compact systems.

A similar approach is needed for the PV & compression concept. At the moment, the compression part is relatively standardized even if with particular specifications (variable cooling power management), the PV modules are standardised as well but the all-in-one system including PV, wiring, electronic connecting (inverter, control), battery storage and compression chiller is not yet standardised at a large market scale.

This is mainly an assembling issue which could permit, as it has been the case for other heating and cooling products (condensing gas boiler, split units, etc..), a very important cost reduction factor (30-40% cost reduction are possible thanks to a packaging “on the shelf” process). In the range of 100 kW_c cooling systems, this standardizing effort could be still valid even if the concept of packaging is more difficult because of the system size. Nevertheless, some manufacturers offer modular container solutions and this trend could be further developed.

Another important aspect for the Arab region: the involvement of local companies in the value chain. By stimulating the Arab region market, some local actors in term of installation, engineering and key components developments would significantly permit a cost reduction. The local manufacturing of the main components of solar cooling systems (collectors, chillers) can be a factor of cost reduction estimated to -5 to -10%, however it has to be noted that this would not be the most significant driving factor (since it is mainly avoiding transportation cost).

Finally, and this aspect should be linked to the R&D effort needed for solar cooling in the Arab region. Until now, solar cooling systems were mainly developed for sunny Mediterranean or even central Europe climatic conditions, not for arid and hot conditions. A very efficient way of global cost reduction (avoiding frequent replacement of components and accelerated aging phenomenon) would be to work on existing standard products from major HVAC markets (US, Europe, China) for the Arab region conditions. This is mainly concerning three identified topics:

- dust and high temperature conditions on the solar production,
- heat rejection,
- cooling storage.

This would be a mid-term cost reduction potential (3 to 5 years minimum) but it could constitute a great opportunity to position a leadership among local companies having a partnership with local and international universities and research centers. As a conclusion, the cost reduction potentials are listed and summarised in the Table 4 below.

Table 4: Cost reduction potentials on solar cooling

Factor	Key indicator evolution (difference between initial situation and new one)	Cost reduction ratio (reference : 2015, on investment)
Sales scaling factor	x10 sales volume	15 to 30%
Size scaling factor	x10 system size from 100 kW_c to 1 MW_c	50 to 70%
Packaging factor	Solar cooling prefabrication (kits of less than 30 kW_c)=	30 to 40%
Local company manufacturing factor	Manufacturing of the main components locally	5 to 10%
Technical innovations factor	Arab region adapted solar production	10 to 30%
	Heat rejection	on
	Cooling storage	Net Present Cost

3. RESOURCE ASSESSMENT

In this chapter the international leaders in solar cooling technologies (public and private research institutions and companies) are identified and listed using the information from the IEA-SHC activities and associations/platforms like Green Chiller Association for Sorption Cooling, IIR-IIF, EU ESTTP platform, etc. In a second step the researchers, research institutions and companies in Arab countries involved or about to be involved in R&D related to solar cooling technologies are investigated and also listed. Therefore, a rapid bibliography of the recent conferences and scientific journals including solar cooling publications was done to complete the identification.

3.1 International solar cooling institutions and companies

An 8-year-old report of the IEA-SHC Task 38 (Figure 23) shows that the number of solar cooling plants in Europe was highly concentrated on Spain, followed by Germany in 2007. During the time of nearly a decade until today, the market for new systems has changed away from Europe. Other countries, like Australia, Austria, China, Germany, Italy or Japan are now the leading countries for the installation of solar cooling systems, as well as international solar cooling institutions and companies. Figure 24 shows the results of this study for cumulative numbers of solar cooling technologies, studies, pilot projects and incentive programs for solar cooling by each analysed country. Table 5 summarizes all identified international research institutions and associations, which are involved in research of solar cooling technologies. Table 6 and Table 7 show the identified international manufacturers of solar cooling chillers and solid and liquid sorption systems, respectively. The data in the tables is based on manufacturer's information.

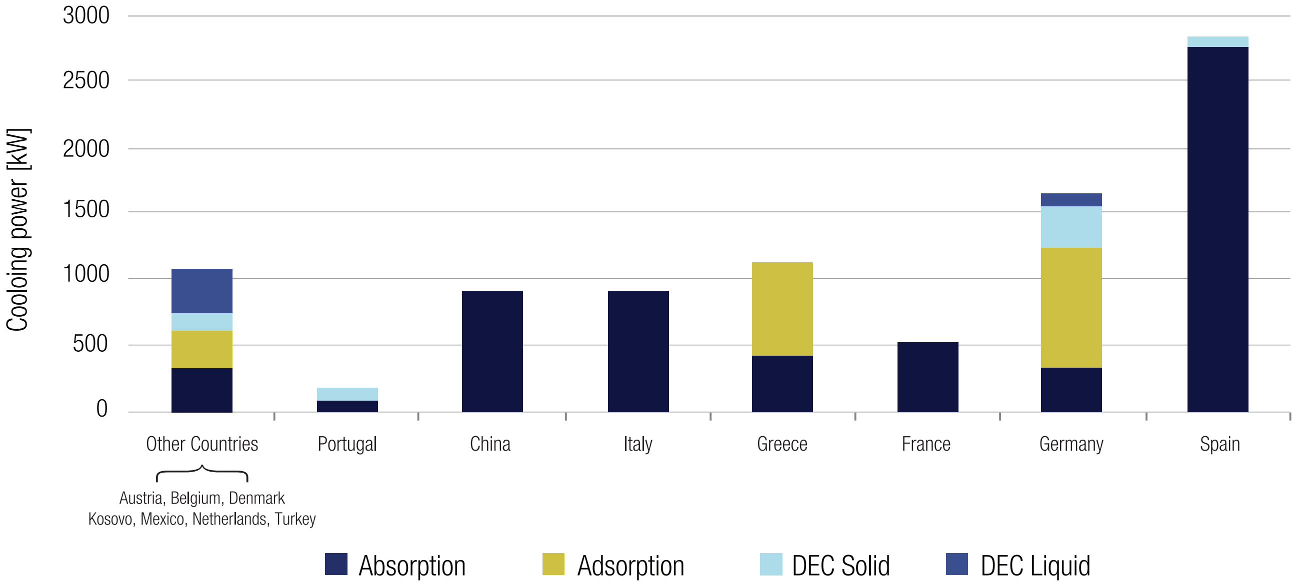


Figure 23: Worldwide distribution of the cooling power assisted by solar energy. The type of thermally driven chillers applied in the different countries is also highlighted (Source: EURAC, [4])

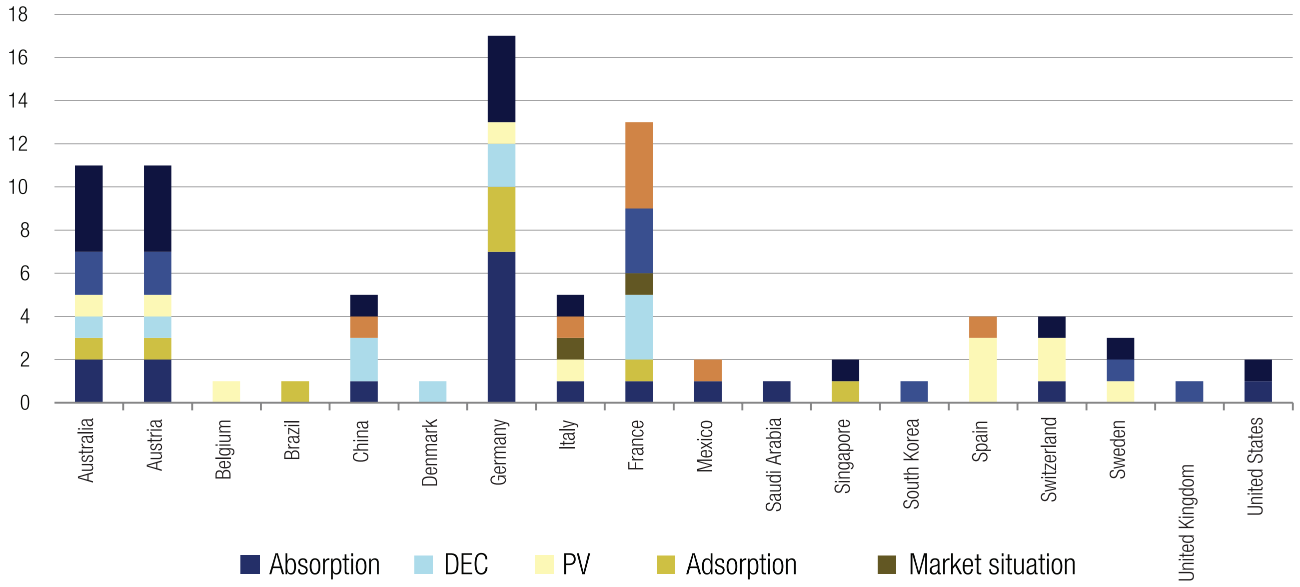


Figure 24: Number of solar cooling technologies, studies, pilot projects and incentive programs by each analysed country (no claim for completeness)

Table 5: International research institutions and associations (no claim for completeness)

Country	Institutions
Austria	AEE-INTEC
	AIT Austrian Institute of Technology
	Technische Universität Graz
	Universität Innsbruck
Canada	Enerworks Inc
	Queen’s University
Denmark	Ellehauge and Kildermoos
France	IIR-IIF
	LOCIE-INES/CNRS
Germany	Fraunhofer ISE
	Fraunhofer IBP
	Fraunhofer UMSICHT
	Green Chiller Association for Sorption Cooling
	ILK Dresden
	Kassel Solar and Systems Engineering University
	TU Berlin
	ZAE Bayern
	zafh.net
Italy	DREAM, University of Palermo
	EURAC
	Politecnico di Milano
Malta	University of Malta
Spain	CARTIF
	CSIC
	Universitat Rovira i Virgili
	UNED
Europe	ESTIF
	EU ESTTP platform
	RHC Renewable Heating & Cooling,

Table 6: Manufacturers of solar cooling chillers (no claim for completeness) [5,8]

Country	Manufacturer	Nominal Cooling Capacity [kW]	Technology	Sorbent / Refrigerant
Austria	Pink	19	ABsorption	H_2O/NH_3
China	BROAD	233	ABsorption	$LiBr/H_2O$
	Jiangsu Huineng	11- 230	ABsorption	$LiBr/H_2O$
	Shuangliang	348	ABsorption	$LiBr/H_2O$
	VICOT	21- 147	ABsorption	H_2O/NH_3
	Shandong Lucy New Energy Technology	11,5- 35	ABsorption	$LiBr/H_2O$
	Shandong Lucy New Energy Technology	5- 50	ADsorption	Silica gel/H_2O
Germany	AGO	50-1000	ABsorption	H_2O/NH_3
	Baelz	50- 160	ABsorption	$LiBr/H_2O$
	EAW	15- 200	ABsorption	$LiBr/H_2O$
	En-Save	30- 100	ABsorption	H_2O/NH_3
	Fischer Eco Solutions	15	ABsorption	$LiBr/H_2O$
	Invensor	4-35	ADsorption	Zeolithe/H_2O
	Köhler Industries	50- 250	ABsorption	H_2O/NH_3
	Meibes System-technik	5	ABsorption	$LiBr/H_2O$
	SorTech	16	ADsorption	Silica gel/H_2O
		13	ADsorption	Zeolithe/H_2O
India	Thermax	17.5- 175	ABsorption	$LiBr/H_2O$
Japan	Mayekawa	105- 215	ADsorption	Silica gel/H_2O
	Mitsubishi Plastics	10	ADsorption	Zeolithe/H_2O
	Sakura	10.5- 17.5	ADsorption	$LiBr/H_2O$
	Yazaki Energy	17.5- 175	ABsorption	$LiBr/H_2O$
Netherlands	SolabCool	5	ABsorption	$LiCl/H_2O$
USA	Energy Concepts LLC	87- 175	ABsorption	H_2O/NH_3
	HIJC	69- 200	ADsorption	Silica gel/H_2O

Table 7: Manufacturers of solid and liquid sorption systems (no claim for completeness) [5,8]

Country	Manufacturer	Nominal Cooling Capacity [kW]	Sorption Technology	Sorbent
Germany	Klingenburg*	350- 35.000 m³/h	Solid	Silica gel / Zeolith
	L-DSC	200- 350	Liquid	LiCl
	Menerga	10- 100	Liquid	LiCl
	Robatherm	16- 307	Solid	Silica gel
	Wolf Geisenfeld	1,6- 30	Solid	Silica gel
USA/Sweden	Munters	N/K	Solid	Silica gel
USA	AIL Research	13- 77	Liquid	$CaCl_2$
	Imtech Drygenic	30- 70	Liquid	LiCl

3.2 Arabic solar cooling institutions and companies

Solar Cooling in the Arab region isn’t at the same level as in Europe, Asia, Australia and America. Mostly the solar irradiation is used to heat the domestic hot water in residential or office buildings. Only a few solar cooling projects have been realized in countries with developed infrastructure, solid economy and no other influences like an instable security, natural disasters or poverty. Other countries are just in the early stage of the development and research of solar cooling. In the following the research institutes and companies are further explained.

Arab region

In member countries like Bahrain, Comoros Island, Djibouti, Libya, Mauritania, Oman, Palestine, Somalia, Syria and Yemen there is currently a very slight or no knowledge about solar cooling. This means that the potential of the establishment and the market, especially in these countries, is high. Most other investigated countries of the Arab region make an effort to supply renewable energies and develop solar cooling. Some of them already have implemented pilot projects with different capacities and usages. The distribution of the currently used solar cooling technologies is shown in Figure 25.

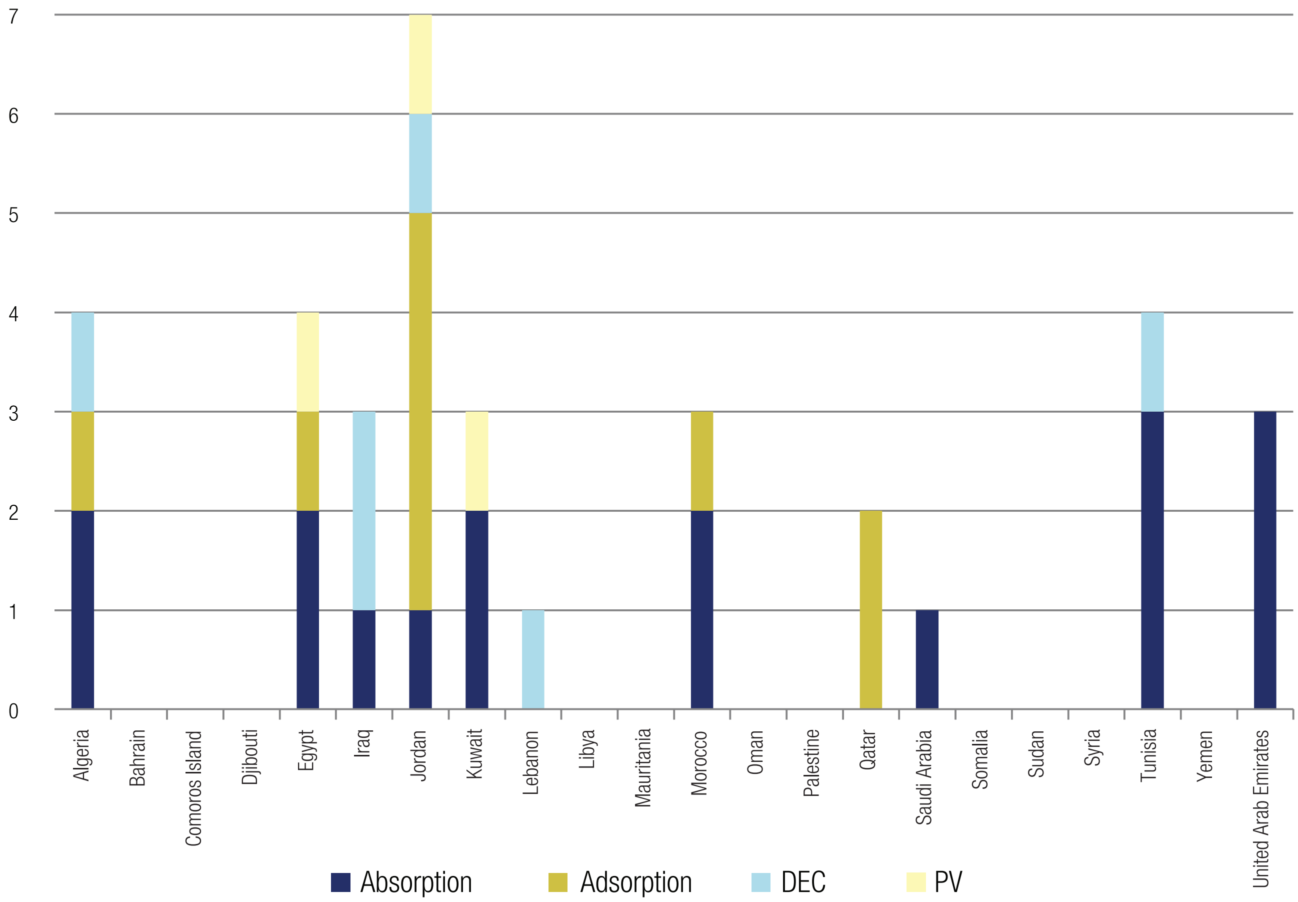


Figure 25: Distribution of solar cooling technologies in the Arab region (studies, pilot projects and incentive programs) by each country (no claim for completeness)
(Source: Solem Consulting)

A detailed description of companies, incentive programs, institutes or (pilot) projects of solar cooling in each of the 22 Arab states is given below:

Kuwait

The development and installation of pilot projects started in the 1980s in Kuwait by the Kuwait Institute for Scientific Research (KISR). One of the first projects was to supply the cooling demand of a school building [14]. Further studies deal with the economy of solar cooling systems in comparison to conventional cooling systems in Kuwait [15]. During the war between Kuwait and Iraq those pilot installations suffered. Solar cooling research was conducted in studies only and since then has not been further promoted.

Algeria

Algeria has an incentive program to stimulate RES that mentions explicit the potential of solar cooling [16, 17]. There are also a lot of recent studies about the topic “Solar Cooling” which are conducted by institutes like the Centre de Développement des Energies Renouvelables (CDER) [18], Unit for Applied Research in Renewable Energies (U.R.A.E.R), Laboratoire de Génie Mécanique (LGM) at the Université de Biskra or the Laboratoire de Génie Energétique et Matériaux (LGEM) at the Université de Biskra [19].

Egypt

Egypt has a lot of institutes that are pushing the research and realizing pilot projects. The EU funded regional project MED-ENEC was very successful. One example is mentioned later in this chapter. The leading institute is the New and Renewable Energy Authority (NREA). In cooperation with the Egyptian Environmental Affairs Agency (EEAA), Egyptian Energy and Environmental Society (EEES) and the Egyptian Solar Energy Society (ESES), a pilot project in Sharm el Sheikh has been implemented. Its purpose is to show the benefits of cooling systems with RES. First energy concept was a double effect absorption chiller with 17.5 kW_c and parabolic linear solar concentrators with outlet temperatures of 160°C. Because of the availability of the absorption chiller and the costs of the parabolic collectors a redesign was necessary.

The technology after the redesign are three applicable single effect absorption chillers with 4.5 kW_c nominal cooling capacity and a total cooling capacity of 24 kW_c from Rotartica. The choose of evacuated tube collectors with 90°C outlet temperature and an area of 82 m^2 was due the more robust technique of this collector type [20, 21]. Due the import of the components from several countries the project was very cost intensive.

Key data of pilot project in Sharm-el-Sheikh/Egypt (EEAA Building):

Chiller capacity / technology:	4 kW_c / water/LiBr absorption chiller
Collector area / technology:	82 m^2 / evacuated tube collectors
Heat rejection capacity / technology	n.a. / directly air-cooled chiller
Storage size:	n.a.
Cold water temperatures:	n.a.

Some of the pilot projects in Egypt are done in cooperation with international companies or research institutes. One example is a demonstration project in Egypt that was projected by the University of Assuit (Egypt) and the Fraunhofer UMSICHT (Germany) [22]. In cooperation with the manufacturer SorTech AG an adsorption chiller with 7.5 kW_c nominal cooling capacity from SorTech AG with silica gel as working pair generates the required cool. Nominal temperatures for heating water between 60-85°C and chilled temperatures between 15-18°C are the process data. The heat is provided by about 40 m^2 of vacuum tube collectors. The heat rejection is realized by a nominal 30 kW evaporative cooling tower from Cofely Refrigeration. In addition a storage tank for hot water with 1,800 l and a 1,600 l chilled water tank are being used.

Key data of pilot project in Egypt with German- Egyptian collaboration:

Chiller capacity / technology	7.5 kWc / silica gel adsorption chiller with
Collector area / technology:	40 m^2 / vacuum tube collectors
Heat rejection capacity / technology:	30 kW / wet cooling tower
Storage size:	hot water 1,800 l / cold water 1,600 l
Cold water temperatures:	15-18°C

For the above mentioned projects, availability of the required components for solar cooling systems was an obstacle. An example for this problem is a project of the Energy Efficiency in the Construction Sector in the Mediterranean (MED-ENEC). The original concept of the 2008 planned system was a double effect absorption chiller in combination with a parabolic linear solar concentrator. Due the unavailability of the components they had to be substituted by a single absorption chiller and evacuated tube collectors [23]. In addition to the research programs of Egypt the government supplies the commitment of RES for the production of electricity, heat and cold by renewable energy tax incentives.

Iraq

At the turn of the millennium, the research on Solar Cooling was very common in Iraq. The Solar Research Center in Baghdad and the Department of Mechanical Engineering of the College of Engineering in Baghdad published studies about the simulation of double effect absorption chillers and DEC-systems [24, 25].

Jordan

The highest numbers of research and pilot projects have taken place in Jordan. Beginning in the year 2007 the institute for Energy Efficiency in the Construction Sector in the Mediterranean (MED-ENEC) started in cooperation with the Jordanian company Millennium Energy Industries (MEI) a pilot project in a residential building in Aqaba. Beside passive measures for decreasing the energy demand, the cooling demand is provided by an adsorption chiller with input temperatures of 55°C [26, 27, 28, 29].

Key data of Aqaba/Jordan project:

Chiller capacity / technology:	15 kWc / silica gel adsorption chiller
Collector capacity / technology:	32 m^2 / evacuated tube collectors
Heat rejection capacity / technology:	40 kW / wet cooling tower
Storage size:	hot water n.a.
Cold water temperatures:	15-18°C

generation project in the MENA region. The MEI chiller can operate at relatively low heat temperatures of 70°C and was patented by MEI. The heat is provided by 40 parabolic trough collectors with 6 m^2 reflector area each and a nominal output of 120 kW_{th} peak. The output temperature of the thermal oil is about 260°C. The adsorption chiller is powered by the rejected heat of the water desalination unit of the tri-generation system [30, 31]

Key data Mu’tah University /Jordan project:

Chiller capacity / technology:	20 kWc / methanol adsorption chiller
Collector area / technology:	240 m^2 / parabolic trough collectors
Heat rejection capacity / technology:	n.a. / dry recooler
Storage size:	n.a.
Cold water temperatures:	12-18°C

Also in 2012 an association of five departments of universities in Jordan realized an adsorption chiller system for solar cooling at the Mango Centre for Scientific research of the University of Amman. Based on the monthly solar radiation data, the collector area was designed. The main goal of the project is the investigation of utilizing solar energy for solar cooling in Jordan. Also the computed payback time of the system will support this aim [31, 32]

Key data Mango Centre/Jordan project:

Chiller capacity / technology:	8 kWc / adsorption chiller
Collector area / technology:	46.5 m^2 / flat plate collectors
Heat rejection capacity / technology:	21 kW / dry recooler
Storage size:	n.a.
Cold water temperatures:	15°C

Jordanian Ministry of Environment (MoEnv), Jordan Ministry for Energy and Mineral Resources (MEMR), International Climate Initiative (ICI), German Federal Ministry for Environment, Nature Conservation and Nuclear Safety (BMU) and the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH started the program "Solar Cooling for Industry and Commerce" in Jordan for the spreading of knowledge of solar-cooling in Jordan. The aim of the program, which ended in early 2015, was to support the training of installation technicians and responsible person for service and maintenance. Further cooperation between German and Jordan technology providers and chiller manufacturers should implement the solar cooling technology in the Jordan. The results of the study will be published [33].

Morocco

In 2008, a collaboration project between the Fraunhofer ISE, POLIMI, Le Bonlait, Abengoa Solar and Tecsol was conducted in Marrakech for milk cooling in a factory. On the roof of the factory parabolic trough collectors provide heat for a 12.8 kW$_c$ single effect absorption chiller. The aperture area of 70 m^2 is distributed on 18 parabolic troughs. If there is no cooling requirement, the cold is stored in a 2 m^3 storage tank which is filled with plastic balls that are filled with water. The ball surrounding fluid is brine. If the temperatures in the storage tank sink below 0°C the water in the plastic balls freezes and stores the cold. [34, 8].

Key data Bonlait milk factory/Morocco project:

Chiller capacity / technology:	12.8 kWc / ammonia/water absorption chiller
Collector area / technology:	70 m^2 / parabolic trough collectors
Heat rejection capacity / technology:	36.6 kW / directly air-cooled chiller
Storage size:	PCM cold storage 2 m^3
Brine temperatures:	-5°C

A study about the great potential of ab- and absorption technologies and their working pairs in Morocco is published by the École Supérieurede Technologie de Fès, Université Sidi Mohamed Ben Abdellah, Ecole Nationale Supérieure des Artset Métiers, ENSAM Marjanell (both Morocco) an the Laboratoire des Sciences del'Ingénieur Appliquées à la Mécanique et au Génie Electrique (SIAME) in France. The paper, that sums up the studies between 2014-2015, considers 6 climate zones in Morocco and is comparative between conventional and solar cooling facing economic and environmental indicators [35, 36].

Qatar

For the FIFA World Cup 2022 in Qatar a showcase soccer stadium with 500 seats was built near to Doha. The solar cooling concept of Arup and Mirroxx (today Industrial Solar) for the stadium is based on double-effect adsorption chillers. The heat is generated by Fresnel collectors with an aperture area of 1,400 m^2 next to the stadium. The chillers have a capacity of about 700 kW$_c$. With this cold the fresh air for the stadium will be cooled and blown in between the seats of the stadium [37].

Key data FIFA World Cup 2022 showcase stadium factory project in Qatar:

Chiller capacity / technology:	700 kWc / double-effect absorption chiller
Collector area / technology:	1,400 m² / Fresnel collectors
Heat rejection capacity / technology:	1.28 MW / wet cooling tower
Storage size:	pressurized water 40 m3 / PCM cold 100 m3
Cold water temperatures:	7-12°C

A study of the Energy Conversation and Air-conditioning Research Group of the University of Qatar in Doha deals with the implementation of an adsorption cooling system in the weather conditions of Qatar. The simulation was carried out with TRNSYS. Capacity of the adsorption chiller is 4.5 kW_c and requires an area of 23.4 m² of evacuated tube collectors. Energy consumption in comparison to a compression chiller can be reduced up to 47% [38].

Abu Dhabi

Two years ago the Abu Dhabi National Energy Company TAQA realized in cooperation with the companies Chromasun and SOLEM Consulting a pilot project for solar cooling with the Chromasun MCT panels. The ground-floor installed collectors are able to generate higher temperatures than flat plate collectors and comparable with the technology of Fresnel collectors. All in all there 27 of this panels installed at the office building and have a total area of about 94 m². The produced heat of the MCT panels is utilized by a double-effect absorption chiller [39].

Key data ADWEA office building in Abu Dhabi:

Chiller capacity / technology:	88 kWc / double-effect absorption chiller
Collector area / technology:	94 m² / MCT collectors
Heat rejection capacity / technology:	161 kW / wet cooling tower
Storage size:	hot water 2.5 m3
Cold water temperatures:	7-12°C

In 2008 the Department of Mechanical Engineering of the University of Maryland in the USA and the Department of Mechanical Engineering of The Petroleum Institute in Abu Dhabi published a study about the feasibility of solar cooling in the climate in Abu Dhabi. The study is based on a simulation in TRNSYS and handles with the air-conditioning of a residential building. The 10 kW_c absorption chiller gets its heat demand by an area of 60 m² of evacuated tube collectors. Result is that the energy consumption can be reduced by 60% in comparison to a vapour compression chiller [42].

The feasibility study for a demonstration project of solar cooling in Masdar City was published 2011 by the New Energy and Industrial Technology Development Organization (NEDO). The research was about a high efficiency solar cooling system with solar collectors and a triple-effect absorption chiller [44].

Another study handles with the performance of an absorption cooling system in the UAE. The system was designed in the Solar Outdoor Laboratory (SOLAB) of the CSEM-uae Innovation Center LLC, AL Jazeera Al Hamra Area, Ras Al Khaimah in the United Arab Emirates [45].

Dubai

In 2010 a solar cooling project was realized in Dubai. The companies Climatewell and Kingspan Renewables build an area of 161 m² vacuum tube collectors to provide heat for six absorption chillers with 10 kW_c each (total 60 kW_c). The chillers cover in average 50% of the cooling demand of an office building with 6,000 m² area (including warehouse and training facility) which is distributed by fan coils. As a back-up system compression chillers are installed. The recooling occurs in a wet cooling tower.

Desalinated sea water provides the water demand of the recooler. The share of solar cooling varies between 30% and 100% depending on the season [43].

Key data office building in Dubai:

Chiller capacity / technology:	60 kWc / 6 water/LiCl absorption chillers
Collector area / technology:	161 m^2 / vacuum tube collectors
Heat rejection capacity / technology:	n.a.
Storage size:	n.a.
Cold water temperatures:	n.a.

Saudi Arabia

The Abdulaziz University-Rabigh published in 2012 a study about the Future of Solar Power Studies and Applications in Saudi Arabia including Solar Cooling. The study mentioned the barriers of solar cooling systems in Saudi Arabia, e.g. reduction of the efficiency up to 20% by dust accumulation, high costs for the construction of solar power system, no incentive programs and political supporting for the research, low energy prices and no involvement of private sectors

Tunisia

A large project in Tunisia is the Grombalia winery. It was planned in the MEDISCO (Mediterranean Solar Cooling) project in 2008. The EU funded project has the aim to develop and realize concepts of solar cooling in the food industry sector. Included partners were the Politecnico di Milano (POLMI), PSE/Mirroxx, ANME, Domain Nefris and Electrosystem. In the hot desert climate Fresnel collectors with an aperture area of 88 m^2 provide the heat for the 12.8 kW_c single effect absorption chiller. As a back-up system a vapour compression chiller is implemented in the system. In addition the system has a 3 m^3 storage tank. With the generated cold three wine storage tanks are cooled. The heat rejection of the chiller is provided by a directly air-cooled- chiller. [8, 46].

Key data Grombalia winery in Tunisia:

Chiller capacity / technology:	
12.8 kWc / ammonia/water absorption chiller	
Collector area / technology:	88 m^2 / Fresnel collectors
Heat rejection capacity / technology:	36.6 kW / directly air-cooled chiller
Storage size:	cold water-glycol 3 m^3
Brine temperatures:	-10°C

At the same time another project was carried out. Like the winery project it was done by a consortium, consisting of Centre des Recherches et des Technologies de l'Energie (CRTEn) and the Institut Supérieur des Sciences Applique´es et de Technologie de Gabes (ISSATG), which are both located in Tunisia. The pilot installation is located on the Center of Researches and Energy Technologies (CRTEn) in Bordj-Cédria in Tunisia. A double effective absorption chiller from the manufacturer Broad Company with a capacity of 16 kW_c supplies cold water for the fan coils in the building. The heat requirement of the chiller is covered by 13.34 m^2 of parabolic trough solar collectors. The maximum measured outlet temperature is 155°C. As a back-up system a gas-fired boiler with a heating capacity of 20 kW could request. The cold distribution in the office building is realized by fan coils.[47].

Key data demo project at Bordj-Cèdria/Tunisia:

Chiller capacity / technology: 16 kWc / double-effect absorption chiller
Collector area / technology: 13.34 m² / parabolic trough collectors
Heat rejection capacity / technology: n.a.
Storage size: n.a.
Cold water temperatures: n.a.

Five years later a collaboration of the Laboratoire des Systems Electo-Mécaniques (LASEM), National Engineering School of Sfax University of Sfax in Tunisia and the College of Engineering at Alkharj, Mechanical Engineering Department, Salman bin Abdelaziz University, Saudi Arabia finished a one year simulation study about the solar cooling condition, especially DEC-systems. The study has a special focus on air conditioning units for offices In 2013 the Research and Technology Center of Energy (CRTEn) and the Energy in Buildings and Solar Energy, National Engineering School of Tunis (ENIT), both located in Tunisia, invested time in the research and a TRNSYS simulation of the energy performance of office buildings in Tunisia which are cooled by solar cooling. For their study they simulated a cooling system with a LiBr absorption chiller with 16 kW. During summer a 39 m² aperture area of parabolic trough solar collectors generate the heat for the chiller [48].

Lebanon

The Department of Mechanical Engineering of the American University of Beirut published in 2011 a study about the feasibility of the usage of solar-powered DEC-systems. In the study they prove a parabolic solar concentrators to provide the heat for the regeneration of the liquid desiccant [49].

Sudan

As early as 1998 the Faculty of Engineering & Architecture of the University of Khartoum worked out in collaboration with the Faculty of Engineering Sciences of the Omdurman Islamic University (both in Sudan) a study about two different types of building constructions. Based on a computer simulation the study has also a focus at the cooling system of the building. For the evaluation of solar cooling in the region of Khartoum a LiBr absorption air conditioner were taken. The heat comes from a flat plate collector [50].

Main conclusions on R&D in the Arab states:

The potential of solar cooling in the Arab region is very high. The bulk of the countries is very engaged to push the implementation of solar cooling and renewable energies forward (Figure 26). But there are still some obstacles like the availability of the systems components in the region, like demonstrated in the example of the EEAA Building in Sharm el Sheikh from the MED-ENEC in Egypt. Another issue is the high cost for planning knowledge, engineering and the technologies themselves. The abovementioned pilot projects in the different countries may give some hope that more solar cooling systems may be implemented in various sectors. Most of the projects so far have been realized in the residential or commercial sector. But also the industrial sector has a high energy saving potential for solar cooling systems.

In general it can be said, that western orientated Arab countries are far ahead in the group of investigated countries. Their research programs and pilot projects are more specific and further developed. But also another aspect is the cooperation of these countries with European countries or companies (Table 8).

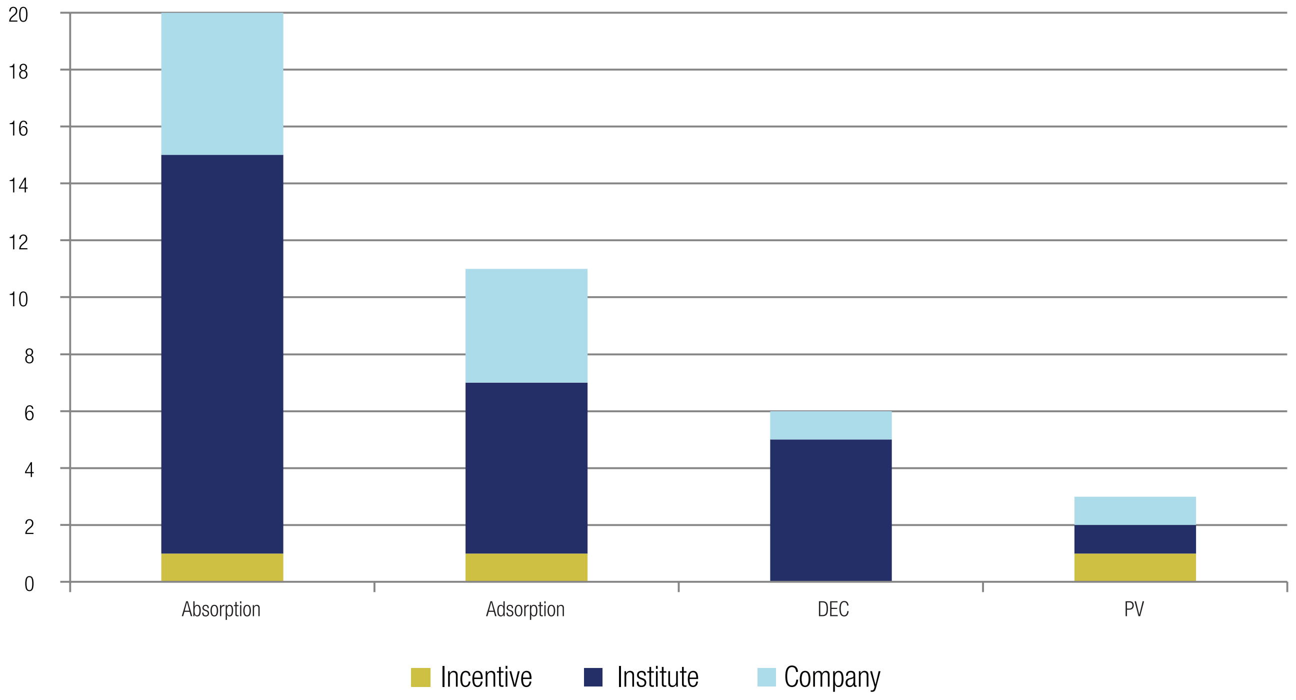


Figure 26: Frequency of solar cooling technologies in incentive programs, institutes and companies in the Arab region (no claim for completeness) (Source: Solem Consulting)

Table 8: List of solar cooling research institutes in the Arab region (no claim for completeness)

Country	Institute
Algeria	CDER- Centre de Développement des Energies Renouvelables
	U.R.A.E.R- Unit for Applied Research in Renewable Energies
	Laboratoire de Génie Mécanique (LGM), Université de Biskra
	Laboratoire de Génie Energétique et Matériaux (LGEM), Université de Biskra
	Agence Nationale pour la Promotion et la Rationalisation de l'Utilisation de l'Energie (APRUE)
Egypt	New and Renewable Energy Authority (NREA)
	Egyptian Environmental Affairs Agency (EEAA)
	Egyptian Energy and Envirnmental Society (EEES)
	Egyptian Solar Energy Sciety (ESES)
	University of Assiut, Egypt
France	Laboratoire des Sciences del'Ingénieur Appliquées à la Mécanique et au Génie Electrique (SIAME), France (in Cooperation with Morocco)
Germany	Fraunhofer UMSICHT, Germany (in Cooperation with Egypt)
	Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) (in Cooperation with Jordan)
	TU Berlin (in Cooperation with Jordan)
	Fraunhofer ISE, Freiburg, Germany (in Cooperation with Morocco)
Iraq	Department of Mechanical Engineering, College of Engineering, University of Baghdad, Iraq
	Solar Research Center, Baghdad, Iraq
Italy	Dip. Energia, Politecnico di Milano, Milan, Italy (in Cooperation with Morocco)

Country	Institute
Jordan	Jordanian Ministry of Environment (MoEnv)
	Jordan Ministry for Energy and Mieral Resources (MEMR)
	International Climate Initiative (ICI)
	Mechanical Engineering Department, The University of Jordan, Jordan
	Energy Center, The University of Jordan, Jordan
	Chemical Engineering Department, The University of Jordan, Jordan
	Hamdi Mango Center, The University of Jordan, Jordan
	Al-Zaytoonah Private University of Jordan, Jordan
Kuwait	Kuwait Institute for Scientific Research (KISR), Kuwait
Lebanon	Department of Mechanical Engineering, American University of Beirut, Lebanon
Morocco	École Supérieurede Technologie de Fès, Université Sidi Mohamed Ben Abdellah, Morocco
	Ecole Nationale Supérieure des Artset Métiers, ENSAM Marjanell, Morocco
Qatar	Energy Conservation and Air-conditioning Research Group, College of Engineering, Qatar University, Doha, Qatar
Saudi Arabia	Abdulaziz University-Rabigh
	Abu Dhabi National Energy Company
	Tunisia College of Engineering at Alkharj, Mechanical Engineering Department, Salman bin Abdelaziz University, Saudi Arabia
Sudan	Faculty of Engineering & Architecture, University of Khatoum, Sudan
	Faculty of Engineering Sciences, Omdurman Islamic University, Sudan
Tunisia	Centre des Recherches et des Technologies de l'Energie (CRTEn), Tunisia
	Institut Supe´rieur des Sciences Applique´es et de Technologie de Gabes (ISSATG), Tunisia
	Energy in Buildings and Solar Energy, National Engineering School of Tunis (ENIT), Tunisia
	Laboratoire des Systems Electo-Mécaniques (LASEM)
	National Engineering School of Sfax University of Sfax
U.A.E.	CSEM-uae Innovation Center LLC, AL Jazeera Al Hamra Area, Ras Al Khaimah, United Arab Emirates
	New Energy and Industrial Technology Development Organization (NEDO)
	Department of Mechanical Engineering, The Petroleum Institute, Abu Dhabi, U.A.E.
U.S.A.	Department of Mechanical Engineering, University of Maryland, College Park, MD, U.S.A. (in Cooperation with U.A.E.)

4. RECOMMENDATIONS FOR POLICY MAKERS

This chapter deals with recommendations to policy makers for the initiation of solar cooling R&D programs and for linking national R&D efforts with international collaboration programs and projects. Therefore, the methodology of “road mapping” from IEA-SHC Task 48 [51] as well as applications in specific countries or regions such as Europe (ESTTP), France (ADEME) and Austria are adapted. On the content point of view of the program, a particular focus is addressed on the locking technological points for Arabic solar cooling developments. These include:

- adapted heat rejection systems,
- improved systems robustness in arid and hot conditions,
- easiness of installation and maintenance,
- building integration and
- compatibility with local electrical grids.

In a second step the annual cost to the public budget of proposed actions (demo and R&D projects) is estimated based on past experiences and knowledge from the scientific community.

4.1 Solar cooling roadmap for Arab region

As it is described in the IEA-SHC Task 48 work on road mapping, a typical solar cooling roadmap process is constituted of four different phases:

A) Initial phase
B) Basic Investigation Phase / Displaying current status
C) Target definition phase
D) Action plan phase

A) and B) have already been addressed in the previous Chapters 1 and 2.
The focus of this chapter is now aimed at defining the main targets (C) for solar cooling in the Arab region as well at describing a proposal of action plan (D).

C) Main targets:

The three main targets identified from the previous part of the study (Chapter 2), that need to be addressed for the solar cooling sector in the Arab region are:

- investment cost reduction,
- overall energy performance increase and
- system quality improvement.

Even further, these three targets can be summarised by one single target: **global system cost reduction and competitiveness on the long term.** From the main targets, a simple objective tree can be drawn using the UNEP methodology of the Theory of Change (UNEP Programme Manual May, 2013). Figure 27 shows a simple problem tree / situation analysis listing all the important facts identified in the previous chapters. This situation analysis converted into a simple objective tree is shown in Figure 28.

In Figure 28, the means are divided into two types of measures: the red boxes are classified as R&D and innovations developments and can be supported by R&D and demo programs. The blue boxes are classified as market accompanying measures. In these schemes, it has to be noted that no information awareness campaign has been included but this could be easily considered as another complementary accompanying measures.

In order to reach these targets, R&D and demonstration programs are very important pillars. In parallel, at the political level, a decision to develop both important training activities to target publics as well to settle a selective inventive scheme would be a very efficient complementary and boosting measure.

D) Action plan:

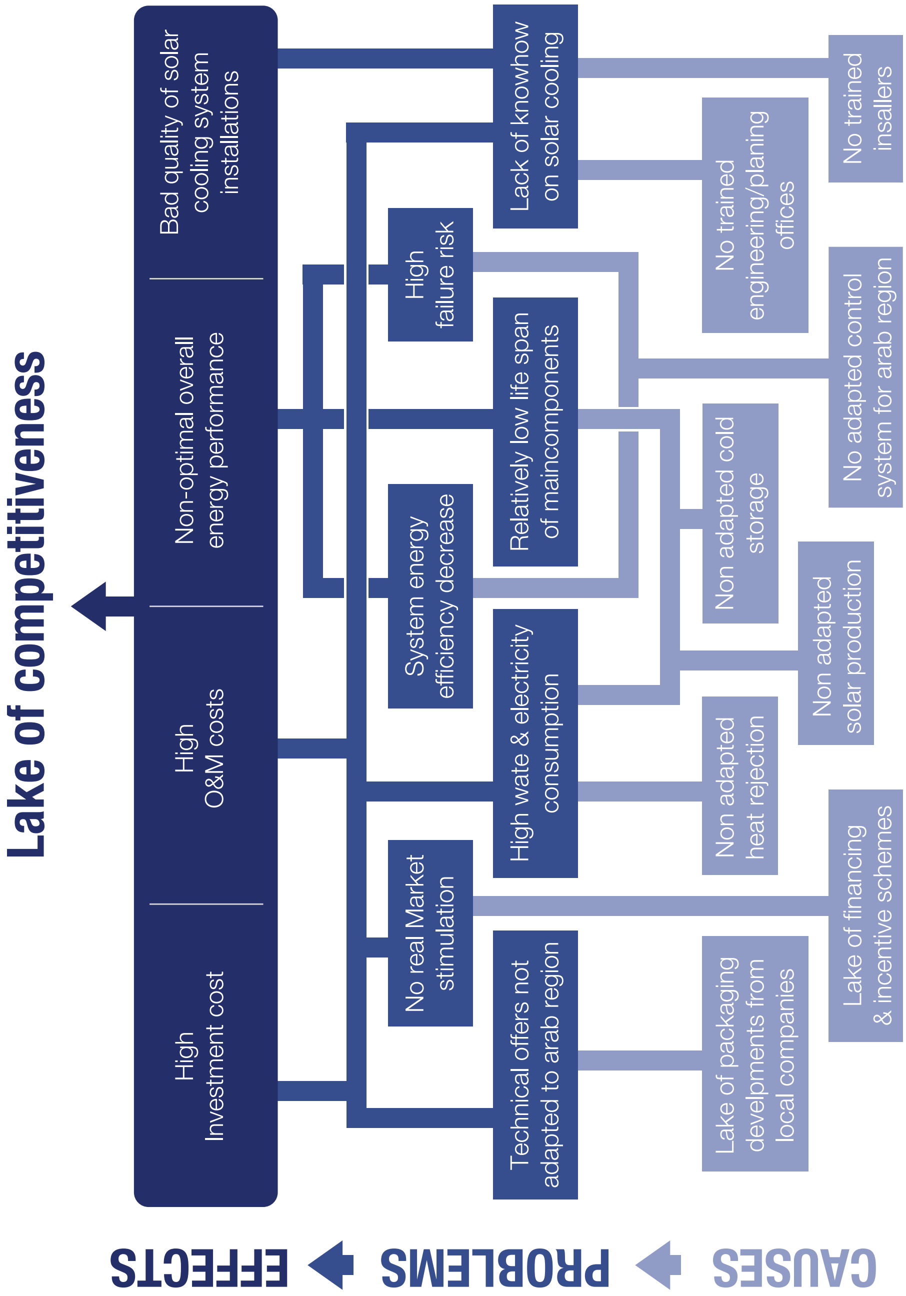


Figure 28: Simple objective tree for solar cooling roadmap in Arab region. Red boxes are classified as R&D and innovations developments and can be supported by R&D and demo programs. Blue boxes are classified as market accompanying measures.

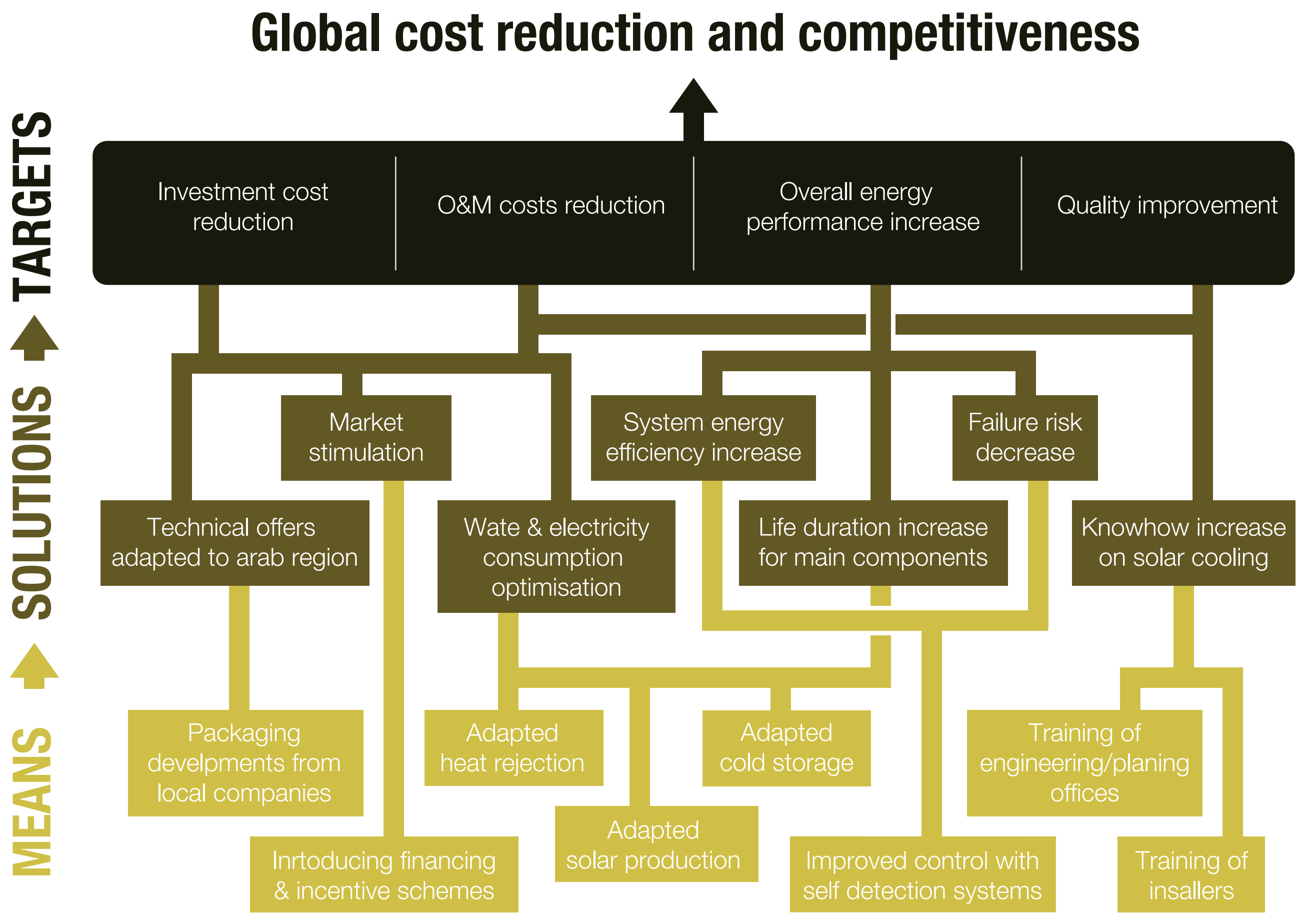


Figure 27: Simple problem tree / situation analysis for solar cooling roadmap in Arab region

4.2 Cost for proposed actions

As described in Chapter 1.2, the costs for small solar cooling systems < 35 kW_c have decreased to approx. 3,750 USD per kW_c (3,500 EUR/kWc) over the recent six years. In order to stimulate the market of SAC significantly more, the investment costs for have to minimized. The analysis of the simple problem tree (Figure 27) and simple objective tree (Figure 28) for the solar cooling roadmap shows that the main proposed actions are focusing on technical issues to overcome the current drawbacks to push the solar cooling technologies in the Arab region.

Financing and incentive schemes actions stimulate the market development, this e.g. can be done by introducing ESCO models (third party financing) or national incentive schemes (e.g. 50% funding for the solar cooling system or tax rebates from the national governments). Successful funded projects like this can be found in Asia (United World College in Singapore, chiller capacity 1,470 kW, 3,872 m^2 collector area) and USA (Desert Mountain High School in Arizona, chiller capacity 1,750 kW, 4,935 m^2 collector area).

Training actions for engineering/planning offices and installers can start in a later phase of the project, if the first pilot installations are installed and commissioned as well as if monitoring data and operating experience are available. Therefore, the following technical actions (R&D and demonstration) are proposed to stimulate the solar cooling development in the Arab region:

- Adapted heat rejection
- Adapted packed solar cooling systems
- Adapted solar production
- Adapted cold storage

The total budget required for the proposed R&D and demonstration programs is divided into 2/3 for R&D and 1/3 for demonstration:

- R&D program for adapting the following technical topics with a proposed budget of 3.0 million USD:
    1. Heat rejection (1.0-1.5 million USD)
    2. Adaption of existing products/kits to Arab region (1.0 million USD)
    3. Storage (0.5-1.0 million USD)
- Demonstration program for PV Cooling and SHC systems with a prosed budget of 1.5 million USD (proposal: two PV Cooling and two SHC system projects):
    1. 100 kW PV Cooling (approx. 200.000 USD for one project)
    2. 1 MW SHC system (approx. 600.000 USD for one project)

The total cost for the proposed actions on R&D and demonstration has been estimated to approx. 4.5 million USD for the development of solar cooling in the Arab region. These actions can lead to a significant share of the cooling supply for buildings and processes as well as CO^2 reduction in the Arab countries in the future.

5. SUMMARY AND OUTLOOK

This study on commercial viability of solar cooling technologies and applications in the Arab region shows a logical pathway to identify the most efficient, reliable and cost competitive solar cooling systems for the Arab region and suggests how to increase the adoption of solar cooling in 22 Arab countries, including RCREEE member states (Algeria, Bahrain, Djibouti, Egypt, Iraq, Jordan, Kuwait, Lebanon, Libya, Mauritania, Morocco, Palestine, Sudan, Syria, Tunisia, United Arab Emirates, Saudi Arabia, Oman, Somalia, Qatar, Comoros Island and Yemen).

Chapter 1 deals with an **overview about the existing solar cooling technologies** in the world (Solar thermal Cooling and PV Cooling), the markets and current available products. The main progress in solar cooling was made in the last decade on the development of small-scale heat driven sorption chillers, the increasing number of high efficient double and triple effect absorption chillers as well as the development of solar cooling systems using single-axis tracking concentrating collectors. But these systems are not optimized for the Arab region so far, where e.g. energy efficient heat rejection systems are necessary where frequently climatic conditions are hot and dry including dusty external environment.

In Chapter 2 of the study, **commercialized solar cooling technologies were identified** and therefore two cases (target buildings in Arab region with a predominant daily cooling load) with **100 kW$_c$ and 1 MW$_c$ cooling capacity** were investigated. In order to cover a large spectrum of markets in the Arab region, the solar cooling technologies will have to be very robust and simple to maintain in predominantly harsh hot and arid conditions. Furthermore, a **life cycle assessment (LCA) at system level adapted for the Arab region characteristics** for a small-scale solar thermal cooling system was done for Tunisia to identify possible primary energy savings and avoided greenhouse gases emissions. As solar cooling technology is having high upfront costs, each produced kWh of cooling needs to be used in the best efficiency. Therefore, the two most economically viable and applicable solar cooling technologies for the Arab region were chosen taken into account the Arab climates, solar irradiation and electricity as well as water costs:

Chosen solar cooling technologies:

- Double-effect absorption chiller and concentrating collectors
- Vapour compression scroll chiller and PV modules

Both investigated technologies are compared with a conventional chiller system to calculate the energy performance related to the use of solar thermal cooling systems instead of conventional and PV ones. It is to be noted that for Comoros Islands as well as Djibouti, Mauritania and Somalia the calculations are not done because solar resource data as well as economic indicators (energy prices) for those four countries was only scarcely available.
For the **100 kW$_c$ range,** the comparative analysis for each of the 18 countries shows very positive results in terms of Net Present Cost (NPC) and Levelised cost of cooling energy (LCCE) for the following six countries:

Favorable countries for a 100 kW$_c$ solar cooling system:

Egypt, Jordan, Morocco, Palestine, Tunisia, Yemen.
There, the net present cost over 20 years of lifetime is lower for both solar cooling technologies compared to the reference case. In all countries above, the PV cooling solution is more competitive than the solar thermal one.

With a 50% subsidy, solar cooling (both PV and thermal) is cheaper than the reference solution in three countries (Oman, Saudi Arabia and UAE). Under these subsidised conditions the difference between solar thermal cooling and solar PV cooling cost is really small. However, in urban areas where available space is limited to settle solar collector fields, solar thermal cooling technology would be preferred.

Finally, **expected cost-reduction resulting from R&D and market expansion** are described in Chapter 2 to stimulate the market deployment of solar cooling in the Arab region. The main drivers are the economy of scale like size of the systems and number of systems sold:

- For a solar thermal cooling system the investment price has been estimated to 3,300 USD/kWc for a 100 kW_c cooling system and to 1,300 USD/kWc for the 1 MW_c cooling system.
- For the PV & compression system, the investment price has been estimated to 2,100 USD/kWc for a 100 kW_c cooling system and to 1,180 USD/kWc for the 1 MW_c cooling system.

Furthermore, the following **R&D requirements have been identified for solar cooling in the Arab region.** The current solar cooling systems were mainly developed for sunny Mediterranean or even central Europe climatic conditions, not for arid and hot conditions. A very efficient way of global cost reduction (avoiding frequent replacement of components and accelerated aging phenomenon) would be to work on existing standard products from major HVAC markets (US, Europe, China) for the Arab region conditions. This is mainly concerning three identified R&D topics:

- Dust and high temperature conditions on the solar production,
- Heat rejection,
- Cooling storage.

Chapter 3 deals with the identification of international leaders in solar cooling technologies (public and private research institutions and companies) as well as researchers, research institutions and companies in Arab countries, which are involved or about to be involved in R&D related to solar cooling technologies. The potential of solar cooling in the Arab region is very high; therefore, a bulk of countries is very engaged to push the implementation of solar cooling and renewable energies forward. But there are still some obstacles like the availability of the systems components in the region. Another issue are the high costs for engineering and the technologies itself. The presented pilot projects in the different Arab countries are targeting to learn about solar cooling systems in various sectors. Most of the projects are in the residential or office sector. In general it can be concluded, that western orientated Arab countries have investigated solar cooling technologies more then the others. A more conducive aspect is also the cooperation of these countries with European countries or companies.

Chapter 4 of this study gives recommendations to policy makers for the initiation of solar cooling R&D programs and for linking national R&D efforts with international collaboration programs and projects as well as an estimation of annual cost to the public budget of proposed actions are presented. Therefore, the following **technical actions (R&D and demonstration)** are proposed to stimulate the solar cooling development in the Arab region:

- Adapted heat rejection,
- Adapted packed solar cooling systems,
- Adapted solar production,
- Adapted cold storage.

The total budget required for the proposed R&D and demonstration programs is divided into 2/3 for R&D and 1/3 for demonstration. **R&D program for adapting the following technical topics** with a proposed budget of 3.0 million USD:

- Heat rejection (1.0-1.5 million USD R&D program),
- Adaption of existing products/kits to Arab region (1.0 million USD R&D program),
- Storage (0.5-1.0 million USD R&D program).

Demonstration program for PV Cooling and Solar thermal Cooling systems with a prosed budget of 1.5 million USD (proposal: two PV Cooling and two SHC system projects):

- 100 kW PV Cooling system (approx. 200.000 USD funding for one project),
- 1 MW Solar thermal Cooling system (approx. 600.000 USD funding for one project).

The cost for the proposed actions on R&D and demonstration will be in total about 4.5 million USD to develop solar cooling for the Arab region. These actions can lead in the future to a significant share of the cooling supply for buildings and processes as well as CO^2 reduction in the Arab countries.

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7. APPENDIX

7.1 Appendix 1

Table 9: Manufacturers of solar thermal collectors (no claim for completeness)

Country	Manufacturer	Technology
Argentina	Energe	Flat-plate
Australia	Solhart	Flat-plate
Austria	CONA	Air collector
	GREENoneTEC	Flat-plate
		Evacuated tube
	ökoTech	Flat-plate
	Solarfocus	Flat-plate
	SST Solar	Flat-plate
Brazil	Enalter	Flat-plate
	Transsen	Flat-plate
Bulgaria	NES	Flat-plate
		Evacuated tube
Canada	enerconcept	Air collector
	Matrix Energy	Air collector
	SolarWall	Air collector
China	Apricus	Flat-plate
		Evacuated tube
	HighTek	Evacuated tube
		Flat-plate
	Himin	Himin
		Evacuated tube
		Parabolic trough
		Fresnel
	Sunrain	Flat-plate
		Evacuated tube
	Sunshore	Evacuated tube
	Tsinghua	Evacuated tube
Croatia	Tehnomont	Flat-plate
Denmark	Arcon	Flat-plate
Finland	PolarSol	Air collector
France	Vaillant	Flat-plate
	Helioclim	Parabolic trough

Country	Manufacturer	Technology
Germany	AkoTec	Evacuated tube
	CitrinSolar	Flat-plate
	Dr. Vetter	Parabolic trough
	Grammer Solar	Air collector
	Industrial Solar	Fresnel
	KBB Solar	Flat-plate
	Narva	Evacuated tube
	Novatec Solar	Fresnel
	Phoenix solar	Evacuated tube
	Pro Target	Parabolic trough
Germany	Ritter Group	Evacuated tube
	Smirro	Parabolic trough
	Solarlite	Parabolic trough
	Solera	Flat-plate
		Evacuated tube
	Solitem	Parabolic trough
	SolMetall	Flat-plate
	Westech Solar	Evacuated tube
Greece	Calpak-Cicero	Flat-plate
	Dimas Solar	Flat-plate
India	Greentek	Flat-plate
	KGDS	Fresnel
	Redren Energy	Evacuated tube
	SLT Energy	Parabolic trough
	Sudarshan	Flat-plate
		Evacuated tube
	Tata Power	Flat-plate
		Evacuated tube
Israel	Chromagen	Flat-plate
	Elsol/Rand	Flat-plate
Italy	Archimede Solar Energy	Parabolic trough
	CSP-F SpA	Fresnel
	Soltigua	Parabolic trough
		Fresnel
	Trivelli Energia	Parabolic trough
	Viessmann	Evacuated tube
Iran	Hanania Solar Energy	Flat-plate
		Fresnel
	NUR Solar	Flat-plate
Kenya	Solimpeks	Flat-plate
Mexico	Modulo Solar	Flat-plate
	Kioto Clear Energy	Flat-plate
Poland	Solar-Tech	Evacuated tube
Portugal	Soldirecto	Flat-plate
Serbia	Elsol	Flat-plate
South Africa	Waterlite	Evacuated tube

Country	Manufacturer	Technology
Spain	Abengoa Solar	Parabolic trough
	BDR Thermea	Flat-plate
	CIEMAT	Parabolic trough
	Hucu Solar	Flat-plate
	SRB Energy Research	Flat-plate
Switzerland	AMK-Solac	Evacuated tube
	NEP Solar	Parabolic trough
	TVP Solar	Flat-plate
		Evacuated tube
Sweden	Absolicon	Parabolic trough
Syria	Altawfeer solar	Evacuated tube
Tunisia	Biome (KBB)	Flat-plate
	Sines	Flat-plate
Turkey	Ezinc	Flat-plate
	Solimpeks	Flat-plate
Ukraine	Sint Solar	Flat-plate
United Kingdom	Kingspan Environmental	Flat-plate
		Evacuated tube
	Viridian	Flat-plate
Uruguay	FUCO	Flat-plate
USA	AET Solar Energy Products	Flat-plate
	Chromasun	Fresnel
	Focal Point Energy	Parabolic trough
	SunEarth	Flat-plate
	Sunmaxx	Flat-plate
		Evacuated tube
	Whitestar Energy	Parabolic trough

7.2 Appendix 2

Data sources for Table 2 and Table 3

Irradiation horizontal and direct normal radiation (Table 2 & 3)):
IRENA (with RCREEE and League of Arab States) „Pan Arab Renewable energy Strategy 2030, Roadmap of actions for Implementation" (2014), p.28 (quoting German Aerospace Center (2005), Concentrating Solar Power for the Mediterranean Region)

PV yield (20° tilt South) (Table2 & 3):
Calculated and retrieved 10 25 2015 from NREL PVWATTS method, http://pvwatts.nrel.gov/pvwatts.php

Electricity cost for commercial (çUSD.kWh) and % of subsidy on electricity tariff for commercial (Table 2):
RCREEE „Arab Future Energy Index, AFEX 2015, Renewable Energy", (2015), Regional Center for Renewable Energy and Energy Efficiency (RCREEE), p.46

Electricity cost for industry (çUSD.kWh) and % of subsidy on electricity tariff for commercial (Table 3):
RCREEE „Arab Future Energy Index, AFEX 2015, Renewable Energy", (2015), Regional Center for Renewable Energy and Energy Efficiency (RCREEE), p.47

Table 10: Water cost (USD/m³) (Table 2 & 3)

Country Source of data (see detailed references below

Country	Source of data (see detailed references below
Algeria	Wikipedia
Bahrain	MEW
Egypt	Wikipedia
Iraq	METI
Jordan	Wikipedia
Kuwait	CEBC
Lebanon	Wikipedia
Libya	FICHTNER
Morocco	LYDEC
Oman	CEBC
Palestine	Wikipedia
Qatar	CEBC
Saudi Arabia	CEBC
Sudan	Authors assumption
Syria	Environmental Engineering
Tunisia	Wikipedia
United Arab Emirates	CEBC
Yemen	Authors assumption

CEBC : „WATER AND ENERGY IN MENA, CHALLENGES, OPPORTUNITIES AND POTENTIAL" report from Clean energy Business Council (2014), http://www.cleanenergybusinesscouncil.com/site/resources/files/Energy-and-Water-in-MENA.pdf, p.14

MEW : retrieved 10 25 2015 from Kingdom of Bahrain Electricity and Water Authority, http://www.mew.gov.bh/default.asp?action=category&id=40

Wikipedia : retrieved 10 26 2015 from Wikipedia website in Category „Water supply and sanitation", https://en.wikipedia.org/wiki/Category:Water_supply_and_sanitation_by_country

METI : „Water and sewage Sectors in Iraq, sector report" (2013), METI

Environmental Engineering : Dr.Eng. Abdulrzzak Alturkmani, retrieved 10 25 2015 from Environmental Engineering website , http://www.4enveng.com/edetails.php?id=35

Authors assumption : by lack of available data and due to similar conditions for water supply market, the water cost is estimated at the same level as the Syrian level.

FICHTNER : „MENA Regional Water Outlook - Part II - Desalination Using Renewable Energy", final report, (2011), FICHTNER, p.6-87

LYDEC : retrieved 10 26 2015 from LYDEC website for tariffs on 01/01/2015, https://client.lydec.ma/site/fr/web/guest/tranches-de-facturation-et-tarifs-pro

7.3 Appendix 3

Assumptions used for the cost calculations (with examples for Tunisia/100 kW cooling and KSA/1MW cooling)

Table 11: Operation and Maintenance costs (example for Tunisia for 100 kW cooling system)

			SOLAR COOLING SYSTEM	PV COOLING SYSTEM	REFERENCE SYSTEM
		UNIT			
Utilities	Electricity price (year 1)	$/kWhel	0,16	0,16	0,16
	Gas price (year 1)	$/kWhth	0,00	0,00	0,00
	Water price (year 1)	$/m^3	0,6	0,6	0,6
	Annual escalation rate of electricity price	%/a	3	3	3
	Annual escalation rate of gas price	%/a	2	2	2
	Annual escalation rate of water price	%/a	1	1	1
Operation	Total electrical power of system (nominal)	kWel	12,9	7,8	47,8
	Full load hours of operation	h/a	2400	2400	2400
	Total annual electricity consumption	kWhel/a	30960	18720	114720
	Total annual gas consumption	kWhth/a	0	0	0
	Total annual water consumption	m^3/a	720	360	360
	Annual electricity cost (year 1)	$/a	$4 954	$2 995	$18 355
	Annual gas cost (year 1)	$/a	$0	$0	$0
	Annual water cost (year 1)	$/a	$432	$216	$216
	Total annual operational cost (year 1)	$/a	$432	$3 211	$18 571
Maintenance	Total annual maintenance cost (year 1)	$/a	$4 000	$5 000	$4 000
O&M	Total annual O&M cost (year 1)	$/a	$9 386	$8 211	$22 571

Table 12: Operation and Maintenance costs (example for KSA for 1MWcooling system)

		UNIT	SOLAR COOLING SYSTEM	PV COOLING SYSTEM	REFERENCE SYSTEM
Utilities	Electricity price (year 1)	$/kWhel	0,041	0,041	0,041
	Gas price (year 1)	$/kWhth	0,00	0,00	0,00
	Water price (year 1)	$/m³	1,6	1,6	1,6
	Annual escalation rate of electricity price	%/a	3	3	3
	Annual escalation rate of gas price	%/a	2	2	2
	Annual escalation rate of water price	%/a	1	1	1
Operation	Total electrical power of system (nominal)	kWel	129	78	478,0
	Full load hours of operation	h/a	2500	2500	2500
	Total annual electricity consumption	kWhel/a	322500	195000	1195000
	Total annual gas consumption	kWhth/a	0	0	0
	Total annual water consumption	m³/a	7500	3750	3750
	Annual electricity cost (year 1)	$/a	$13 223	$7 995	$48 995
	Annual gas cost (year 1)	$/a	$0	$0	$0
	Annual water cost (year 1)	$/a	$12 000	$6 000	$6 000
	Total annual operational cost (year 1)	$/a	$25 223	$13 995	$54 995
Maintenance	Total annual maintenance cost (year 1)	$/a	$4 000	$5 000	$4 000
O&M	Total annual O&M cost (year 1)	$/a	$29 223	$18 995	$58 995

Table 13: Example of Investment costs for the 100 kWcooling solar thermal cooling system in Tunisia

	SOLAR COOLING SYSTEM	UNIT	TYPE/SIZE	QUANTITY	SPECIFIC COST ($/ UNIT)		
Solar field and hot water circuit	Collectors	m^2	Concentrating parabolic	276	$600	$165 490	
	Piping	m	DN 60	30	$65		$1 950
	Piping	m	DN 50	20	$50		$1 000
	Piping	m	DN 40	20	$50		$1 000
	Pipe Lagging	m	DN 60	30	$65		$1 950
	Pipe Lagging	m	DN50	20	$50		$1 000
	Pipe Lagging	m	DN 40	20	$50		$1 000
	Solar circuit pump	m^3/hr	6	1	$3 000		$3 000
	Valves miscellaneous	-		1	$500		$500
	Heat exchanger	-	Plate	1	$1 500		$1 500
	Expansion tank and safety relief valve	-		1	$300		$300
	Hot water circuit pump	m^3/hr	7,2	1	$2 500		$2 500
	Valves miscellaneous	-		1	$400		$400
	Expansion tank and safety relief valve	-		1	$300		$300
	Hot water storage tank incl. Insulation	m^3	7,5	1	$20 000	$20 000	
	Piping	m	DN 60	20	$65		$1 300
	Pipe Lagging	m	DN 60	20	$65		$1 300
Thermal chiller and chiller circuits	Absorption chiller	kW_r	100	1	$70 000	$70 000	
	Cooling tower	kW_{th}	191	1	$30 000	$30 000	
	Cooling water pump	m^3/hr	24	1	$3 000		$3 000
	Valves miscellaneous	-		1	$200		$200
	Piping	m	DN 40	50	$50		$2 500
	Pipe Lagging	m	DN 40	50	$50		$2 500
	Chilled water pump	m^3/hr	12,6	1	$2 500		$2 500
	Valves miscellaneous	-		1	$200		$200
	Expansion tank and safety relief valve	-		1	$300		$300
	Piping	m	DN 60	50	$65		$3 250
	Pipe Lagging	m	DN 60	50	$65		$3 250
Instruments and control	Sensors/Gauges	-	Temp/Radiation/Pressure	10	$100		$1 000
	Controller/System PLC	-	PLC	1	$10 000		$10 000
	Total cost (Main Component/BoP)				SUM	$285 490	$47 700
	Percentage (Main Component/BoP)					86%	14%
	Total Cost System					$333 190	

Table 14: Example of Investment costs for the 100 kWcooling solar PV cooling system in Tunisia

	PV COOLING SYSTEM	UNIT	TYPE/ SIZE	QUANTITY	SPECIFIC COST ($/ UNIT)	MAIN COMPONENT COST	BALANCE OF PLANT COST
PV system	PV field + structure	kWp	70,6	1	$42 353	$42 353	
	Wiring			1	$10 000	$10 000	
	Inverter	kVA	78	1	$15 529	$15 529	
	battery storage	kWh	35	1	$21 176	$21 176	
	BOS			1			$23 882
Conventional chiller and chiller circuits	Reversible Vapour compression chiller, screw type	kW_r	100	1	$70 000	$70 000	
	Cooling tower	kW_{th}	45	1	$15 000	$15 000	
	Cooling water pump	m^3/hr	5,5	1	$2 500		$2 500
	Valves miscellaneous	-		1	$200		$200
	Piping	m	DN 60	50	$65		$3 250
	Pipe Lagging	m	DN 60	50	$65		$3 250
	Chilled water pump	m^3/hr	4,2	1	$2 500		$2 500
	Valves miscellaneous	-		1	$200		$200
	Expansion tank and safety relief valve	-		1	$150		$150
	Piping	m	DN 32	50	$45		$2 250
	Pipe Lagging	m	DN 32	50	$45		$2 250
Instruments and control	Sensors/Gauges	-	Temp/ Pressure	5	$100		$500
	Controller/System PLC	-	PLC	1	$10 000		$10 000
	Total cost (Main Component/ BoP)				SUM	$174 059	$50 932
	Percentage (Main Component/BoP)					77%	23%
	Total Cost System					$224 991	

Table 15: Example of Investment costs for the 100 kWcooling refrence system in Tunisia

	REFERENCE SYSTEM	UNIT	TYPE/ SIZE	QUANTITY	SPECIFIC COST ($/ UNIT)	MAIN COMPONENT COST	BALANCE OF PLANT COST
Conventional chiller and chiller circuits	Reversible Vapour compression chiller, screw type	kW_r	100	1	$70 000	$70 000	
	Cooling tower	kW_{th}	45	1	$15 000	$15 000	
	Cooling water pump	m^3/hr	5,5	1	$2 500		$2 500
	Valves miscellaneous	-		1	$200		$200
	Piping	m	DN 60	50	$65		$3 250
	Pipe Lagging	m	DN 60	50	$65		$3 250
	Chilled water pump	m^3/hr	4,2	1	$2 500		$2 500
	Valves miscellaneous	-		1	$200		$200
	Expansion tank and safety relief valve	-		1	$150		$150
	Piping	m	DN 60	50	$65		$3 250
	Pipe Lagging	m	DN 60	50	$65		$3 250
Instruments and control	Sensors/Gauges	-	Temp/ Pressure	5	$100		$500
	Controller/System PLC	-	PLC	1	$5 000		$5 000
	Total cost (Main Component/ BoP)				SUM	$85 000	$24 050
	Percentage (Main Component/BoP)					78%	22%
	Total Cost System					$109 050	
Instruments and control	Sensors/Gauges	-	Temp/ Pressure	5	$100		$500
	Controller/System PLC	-	PLC	1	$10 000		$10 000
	Total cost (Main Component/ BoP)				SUM	$174 059	$50 932
	Percentage (Main Component/BoP)					77%	23%
	Total Cost System					$224 991	

Table 16: Example of Investment costs for the 1 MWcooling solar thermal cooling system in KSA

	SOLAR COOLING SYSTEM	UNIT	TYPE/SIZE	QUANTITY	SPECIFIC COST ($/UNIT)	MAIN COMPONENT COST	BALANCE OF PLANT COST
PV system	Collectors	m^2	Concentrating parabolic	2460	$300	$737 898	
	Piping	m	DN 150	300	$80		$24 000
	Piping	m	DN 100	200	$70		$14 000
	Piping	m	DN 80	200	$70		$14 000
	Pipe Lagging	m	DN 150	300	$80		$24 000
Conventional chiller and chiller circuits	Pipe Lagging	m	DN100	200	$70		$14 000
	Pipe Lagging	m	DN 80	200	$70		$14 000
	Solar circuit pump	m^3/hr	60	1	$10 000		$10 000
	Valves miscellaneous	-		1	$2 500		$2 500
	Heat exchanger	-	Plate	1	$10 000		$10 000
	Expansion tank and safety relief valve	-		1	$5 000		$5 000
	Hot water circuit pump	m^3/hr	72	1	$12 000		$12 000
	Valves miscellaneous	-		1	$3 000		$3 000
	Expansion tank and safety relief valve				$5 000		$5 000
	Hot water storage tank incl. Insulation				$50 000	$50 000	
	Piping						$16 000

	SOLAR COOLING SYSTEM	UNIT	TYPE/SIZE	QUANTITY	SPECIFIC COST ($/ UNIT)	MAIN COMPONENT COST	BALANCE OF PLANT COST
Instruments and control	Pipe Lagging	m	DN 150	200	$80		$16 000
	Absorption chiller	kW_r	1000	1	$180 000	$180 000	
	Cooling tower	kW_{th}	1909	1	$60 000	$60 000	
	Cooling water pumpw	m^3/hr	240	1	$20 000		$20 000
	Valves miscellaneous	-		1	$5 000		$5 000
	Piping	m	DN 250	200	$120		$24 000
	Pipe Lagging	m	DN 250	200	$120		$24 000
	Chilled water pump	m^3/hr	126	1	$15 000		$15 000
	Valves miscellaneous	-		1	$3 000		$3 000
	Expansion tank and safety relief valve	-		1	$5 000		$5 000
	Piping	m	DN 200	200	$100		$20 000
	Pipe Lagging	m	DN 200	200	$100		$20 000
Instruments and control	Sensors/ Gauges	-	Temp/Radiation/Pressure	20	$100		$2 000
	Controller/ System PLC	-	PLC	1	$20 000		$20 000
	Total cost (Main Component/BoP)				SUM	$1 027 898	$341 500
	Percentage (Main Component/BoP)					75%	25%
	Total Cost System					$1 369 398	

Table 17: Example of Investment costs for the 1 MWcooling solar PV cooling system in KSA

	PV COOLING SYSTEM	UNIT	TYPE/ SIZE	QUANTITY	SPECIFIC COST ($/ UNIT)	MAIN COMPONENT COST	BALANCE OF PLANT COST
PV system	PV field + structure	kWp	609,6	1	$335 264	$335 264	
	Wiring			1	$10 000	$10 000	
	inverter	kVA	671	1	$134 105	$134 105	
	battery storage	kWh	305	1	$121 914	$121 914	
	BOS			1			$252 115
Conventional chiller and chiller circuits	Reversible Vapour compression chiller, screw type	kW_r	1000	1	$144 000	$144 000	
	Cooling tower	kW_{th}	1344	1	$36 000	$36 000	
	Cooling water pump	m^3/hr	165	1	$15 000		$15 000
	Valves miscellaneous	-		1	$5 000		$5 000
	Piping	m	DN 200	200	$100		$20 000
	Pipe Lagging	m	DN 200	200	$100		$20 000
	Chilled water pump	m^3/hr	126	1	$15 000		$15 000
	Valves miscellaneous	-		1	$5 000		$5 000
	Expansion tank and safety relief valve	-		1	$5 000		$5 000
	Piping	m	DN 200	200	$100		$20 000
	Pipe Lagging	m	DN 200	200	$100		$20 000
Instruments and control	Sensors/Gauges	-	Temp/ Pressure	10	$100		$1 000
	Controller/System PLC	-	PLC	1	$20 000		$20 000
	Total cost (Main Component/ BoP)				SUM	$781 283	$398 115
	Percentage (Main Component/BoP)					66%	34%
	Total Cost System					$1 179 398	

Table 18: Example of Investment costs for the 1 MWcooling reference system in KSA

	REFERENCE SYSTEM	UNIT	TYPE/ SIZE	QUANTITY	SPECIFIC COST ($/ UNIT)	MAIN COMPONENT COST	BALANCE OF PLANT COST
Conventional chiller and chiller circuits	Reversible Vapour compression chiller, screw type	kW$_r$	1000	1	$144 000	$144 000	
	Cooling tower	kW$_{th}$	1344	1	$36 000	$36 000	
	Cooling water pump	m^3/hr	165	1			$15 000
	Valves miscellaneous	-		1	$5 000		$5 000
	Piping	m	DN 200	200	$100		$20 000
	Pipe Lagging	m	DN 200	200	$100		$20 000
	Chilled water pump	m^3/hr	126	1	$2 500		$2 500
	Valves miscellaneous	-		1	$5 000		$5 000
	Expansion tank and safety relief valve	-		1	$5 000		$5 000
	Piping	m	DN 200	200	$100		$20 000
	Pipe Lagging	m	DN 200	200	$100		$20 000
Instruments and control	Sensors/Gauges	-	Temp/ Pressure	10	$100		$1 000
	Controller/System PLC	-	PLC	1	$10 000		$10 000
	Total cost (Main Component/BoP)				SUM	$180 000	$123 500
	Percentage (Main Component/BoP)					59%	41%
	Total Cost System					$303 500	

Assumptions used for the sizing calculations (with examples for Tunisia/100 kWcooling and KSA /1MWcooling)

Table 19: Example: 100 kW solar thermal cooling system in Tunisia

	SOLAR COOLING SYSTEM	Unit	TYPE/SIZE	QUANTITY
Solar field and hot water circuit	Solar collector aperture area	m^2	1000	1
	Thermal power (nominal)	kW_{th}	1344	1
	Collector efficiency at 800 W/m^2	%	165	1
	Annual solar gain	MWh_{th}/a		1
	Collector tilt	° from horizontal	DN 200	200
	Azimuth	° from South	DN 200	200
	Solar field flow rate (nominal)	m^3/hr	126	1
	Location	-		1
	Hot water storage tank size	m^3		1
Thermal chiller and chiller circuits	Chiller cooling capacity (nominal)	kW_r	DN 200	200
	COP (nominal)	-	DN 200	200
	Driving energy (nominal)	kW_{th}	Temp/Pressure	10
	Hot water temperature	°C (°F)	PLC	1
	Hot water flow rate	m^3/hr		
	Chilled water temperature	°C (°F)		
	Chilled water flow rate	m^3/hr		
	Cooling water temperature	°C (°F)		
	Cooling water flow rate	m^3/hr		
	Cooling tower capacity (nominal)	kW_{th}		
	Cooling tower type	-		
	Cooling tower fan control	-		
	Water consumption (nominal)	m^3/hr		
Loads	Annual chilled water load	MWh_{th}/a		
	Annual hot water load	MWh_{th}/a		
	Full load hours of system operation	h/a		
Auxiliary power and water consumption	Solar circuit pump	kWel		
	Hot water circuit pump	kWel		
	Thermal chiller	kWel		
	Cooling water pump	kWel		
	Cooling tower fan	kWel		
	Chilled water pump	kWel		
	Control and monitoring	kWel		

Table 20: Example: 100 kW solar PV cooling system in Tunisia

	PV COOLING SYSTEM	Unit	Quantity
PV array & battery	PV primary yearly yield	kWh/kWp.y	1600
	PV losses (dust, storage)	%	15%
	PV useful yield	kWh/kWp.y	1360
	PV array size	kWp	70,6
	PV array area	m^2	543
	Inverter	kVA	78
	Battery	kWh	35
Conventional chiller and chiller circuits	Chiller cooling capacity (nominal)	kW_r	100
	COP (nominal)	-	2,5
	Driving energy (nominal)	kWel	40,0
	Chilled water temperature	°C (°F)	In 14 (57) - Out 7 (45)
	Chilled water flow rate	m^3/hr	12,6
	Cooling water temperature	°C (°F)	In 39 (102) - Out 32 (91)
	Cooling water flow rate	m^3/hr	16,5
	Cooling tower capacity (nominal)	kW_{th}	140
	Type	-	Wet, closed loop
	Water consumption (nominal)	z/hr	0,15
	Fan control	-	Variable speed
Loads	Annual chilled water load	MWh_{th}/a	240
	Annual hot water load	MWh_{th}/a	0
	Full load hours of system operation	h/a	2400
Auxiliary power and water consumption	Cooling water pump	kWel	2,4
	Cooling tower fan	kWel	3,0
	Chilled water pump	kWel	1,8
	Control and monitoring	kWel	0,6
Auxiliary power and water consumption	Solar circuit pump	kWel	
	Hot water circuit pump	kWel	
	Thermal chiller	kWel	
	Cooling water pump	kWel	
	Cooling tower fan	kWel	
	Chilled water pump	kWel	
	Control and monitoring	kWel	

Table 21: Example: 100 kW reference cooling system in Tunisia

	REFERENCE SYSTEM	Unit	Quantity
Conventional chiller and chiller circuits	Chiller cooling capacity (nominal)	kW_r	100
	COP (nominal)	-	2,5
	Driving energy (nominal)	kWel	40,0
	Chilled water temperature	°C (°F)	In 14 (57) - Out 7 (45)
	Chilled water flow rate	m^3/hr	4,2
	Cooling water temperature	°C (°F)	In 39 (102) - Out 32 (91)
	Cooling water flow rate	m^3/hr	5,5
	Cooling tower capacity (nominal)	kW_{th}	140
	Type	-	Wet, closed loop
	Water consumption (nominal)	m^3/hr	0,15
	Fan control	-	Variable speed
Loads	Annual chilled water load	MWh_{th}/a	240
	Annual hot water load	MWh_{th}/a	0
	Full load hours of system operation	h/a	2400
Auxiliary power and water consumption	Cooling water pump	kWel	2,4
	Cooling tower fan	kWel	3,0
	Chilled water pump	kWel	1,8
	Control and monitoring	kWel	0,6
	Annual chilled water load	MWh_{th}/a	240
	Annual hot water load	MWh_{th}/a	0
	Full load hours of system operation	h/a	2400
	Cooling water pump	kWel	2,4
	Cooling tower fan	kWel	3,0
	Chilled water pump	kWel	1,8
	Control and monitoring	kWel	0,6

Table 22: Example: 1 MW solar thermal cooling system in KSA

	SOLAR COOLING SYSTEM	Unit	Quantity
Solar field and hot water circuit	Solar collector aperture area	m^2	2460
	Thermal power (nominal)	kW_{th}	909
	Collector efficiency at 800 W/m^2	%	46
	Annual solar gain	MWh_{th}/a	2841
	Collector tilt	° from horizontal	20
	Azimuth	° from South	49 West
	Solar field flow rate (nominal)	m^3/hr	60,0
	Location	-	KSA
	Hot water storage tank size	m^3	7,5
Thermal chiller and chiller circuits	Chiller cooling capacity (nominal)	kW_r	1000
	COP (nominal)	-	1,1
	Driving energy (nominal)	kW_{th}	909,1
	Hot water temperature	°C (°F)	In 180 (356) - Out 164 (327)
	Hot water flow rate	m^3/hr	51
	Chilled water temperature	°C (°F)	In 14 (57) - Out 7 (45)
	Chilled water flow rate	m^3/hr	126
	Cooling water temperature	°C (°F)	In 39 (102) - Out 32 (91)
	Cooling water flow rate	m^3/hr	240,0
	Cooling tower capacity (nominal)	kW_{th}	1909
	Cooling tower type	-	Wet, closed loop
	Cooling tower fan control	-	Variable speed
	Water consumption (nominal)	m^3/hr	3
Loads	Annual chilled water load	MWh_{th}/a	2500
	Annual hot water load	MWh_{th}/a	0
	Full load hours of system operation	h/a	2500
Auxiliary power and water consumption	Solar circuit pump	kWel	12
	Hot water circuit pump	kWel	12
	Thermal chiller	kWel	27
	Cooling water pump	kWel	24
	Cooling tower fan	kWel	30,0
	Chilled water pump	kWel	18,0
	Control and monitoring	kWel	6

Table 23: Example: 1 MW solar PV cooling system in KSA

	PV COOLING SYSTEM	Unit	Quantity
PV array & battery	PV primary yearly yield	kWh/kWp.y	1930
	PV losses (dust, storage)	%	15%
	PV useful yield	kWh/kWp.y	1640,5
	PV array size	kWp	609,6
	PV array area	m^2	4689
	Inverter	kVA	671
	Battery	kWh	305
Conventional chiller and chiller circuits	Chiller cooling capacity (nominal)	kW_r	1000
	COP (nominal)	-	2,5
	Driving energy (nominal)	kWel	400,0
	Chilled water temperature	°C (°F)	In 14 (57) - Out 7 (45)
	Chilled water flow rate	m^3/hr	126
	Cooling water temperature	°C (°F)	In 39 (102) - Out 32 (91)
	Cooling water flow rate	m^3/hr	165
	Cooling tower capacity (nominal)	kW_{th}	1400
	Type	-	Wet, closed loop
	Water consumption (nominal)	m^3/hr	1,5
	Fan control	-	Variable speed
Loads	Annual chilled water load	MWh_{th}/a	2500
	Annual hot water load	MWh_{th}/a	0
	Full load hours of system operation	h/a	2500
Auxiliary power and water consumption	Cooling water pump	kWel	24
	Cooling tower fan	kWel	30,0
	Chilled water pump	kWel	18
	Control and monitoring	kWel	6

Table 24: Example: 1 MW reference cooling system in KSA

	REFERENCE SYSTEM	Unit	Quantity
Conventional chiller and chiller circuits	Chiller cooling capacity (nominal)	kW_r	1000
	COP (nominal)	-	2,5
	Driving energy (nominal)	kWel	400,0
	Chilled water temperature	°C (°F)	In 14 (57) - Out 7 (45)
	Chilled water flow rate	m^3/hr	126
	Cooling water temperature	°C (°F)	In 39 (102) - Out 32 (91)
	Cooling water flow rate	m^3/hr	165
	Cooling tower capacity (nominal)	kW_{th}	1400
	Type	-	Wet, closed loop
	Water consumption (nominal)	m^3/hr	1,5
	Fan control	-	Variable speed
Loads	Annual chilled water load	MWh_{th}/a	2500
	Annual hot water load	MWh_{th}/a	0
	Full load hours of system operation	h/a	2500
Auxiliary power and water consumption	Cooling water pump	kWel	24
	Cooling tower fan	kWel	30,0
	Chilled water pump	kWel	18
	Control and monitoring	kWel	6
Loads	Annual chilled water load	MWh_{th}/a	2500
	Annual hot water load	MWh_{th}/a	0
	Full load hours of system operation	h/a	2500
Auxiliary power and water consumption	Cooling water pump	kWel	24
	Cooling tower fan	kWel	30,0
	Chilled water pump	kWel	18
	Control and monitoring	kWel	6

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