

# Solar-driven Refrigerator for off-grid Regions

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**Abstract.** Refrigeration systems are necessary for people living in hot climates. A majority of tropical and subtropical countries uses electrical power as a source of cooling. During the seasons of high ambient temperature there is a significant cooling load due to increased level of energy consumption. Cooling systems are therefore necessary in African countries in order to keep medications and food in safe conditions. Furthermore, there is a power shortage crisis due to the high demand for cooling. TRNSYS software allows to simulate a complete solar-powered absorption cooling system. A model used in an experiment includes PV modules making it advantageous over a conventional cooling system. PV modules of assumed area are sufficient to maintain the temperature inside cooling device below 6°C over the whole year.

## 1 Introduction

### 1.1 Solar Systems for domestic cooling meet the increasing demand for air conditioning

Energy consumed for domestic cooling and air-conditioning constitutes significant share in energy demand of the buildings. Since the buildings are responsible for approximately 40% of the global energy consumption [1], situation on the energy market is noticeably affected by requirement for cooling and air-conditioning [1]. Studies have shown a rapid increase in the air-conditioning market around the world and predict further development. Additionally, capability of passive cooling has been restrained by global warming [2]. Those factors contribute to increasing amount of energy consumed for the purpose of cooling and air-conditioning worldwide. In order to meet progressively more restrictive environmental goals established among the international community, i.e. reduction of primary energy consumption and greenhouse gases emission, a wide range of systems for cooling and air-conditioning based on renewable or waste energy has been proposed. One of the most suitable option among other renewable energy sources is solar energy, as top air-conditioning demand overlaps with the highest solar irradiance [3].

Compared to cooling systems powered solely by the public power grid, solar-driven systems are seen as more environment-friendly alternative [4]. These are able to utilize solar energy and therefore to lower the primary energy consumption. It is estimated that deployment of solar cooling systems in southern European and Mediterranean regions could lead to 40-50% savings of primary energy [5]. Introduction of solar cooling systems also allows to avoid some drawbacks of the regular grid-

powered vapour compression-based machines. Classic VC machines significantly burden the grid over the periods of greatest cooling demand, whereas solar cooling systems diminish grid peak load [1, 6]. That feature is considered as convenient particularly during summers when the largest demand for cooling occurs [7]. Such a coincidence between cooling demand and availability of solar energy is the reason why solar cooling is a raising technology, arguably with greater potential than solar domestic heating [8].

Several studies indicate that deployment of solar cooling could be particularly suitable in tropical or subtropical areas [5]. Solar-based cooling systems are identified as promising technology in some regions of Asia, especially in the countries geographically aligned with equator as they take advantage of abundant solar energy [9].

### 1.2 Development of multifunctional solar cooling systems

It is reported that solar cooling systems are almost always multifunctional and are used not only for cooling but also for supplying hot water and domestic heating off-season [5, 10]. That feature makes solar cooling more profitable [1]. Number of reported solar cooling system installed worldwide is around 1200 (as for 2014) and is expected to increase due to quick development of solar cooling technology [1]. Taking into account that usually solar cooling systems are also heating systems, from now on they will be referred to as solar heating and cooling systems (SHC).

Given that multiple solar technologies are available, SHC systems differ in utilised method of harvesting solar energy which may be obtained with

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photovoltaic solar panels or with solar thermal collectors [7]. Further classification of SHC systems is based on distinction if the cooling effect is provided with electrically-driven or thermally-driven process [1, 7]. Electrically-driven cooling is usually achieved by utilising vapour compression cycle and/or heat pumps [7]. Thermally-driven cooling technologies include absorption and adsorption chillers, ejector cycles as well as solid/liquid desiccant cycles [1, 5, 7-11]. Thermally-driven cooling requires heat source and thus could be realised either with PV solar panels or solar thermal collectors. As the main interest of the article is absorption cooling technology, it will be discussed more specifically to the extent necessary later on. Amongst listed SHC layouts the most popular one includes thermally-driven chiller and solar thermal collector combined with a thermal storage system [7].

The main obstacle restraining development of SHC is high capital cost of those installations. If reasonable economic profitability is to be achieved, high capital cost must be balanced with low operating cost [7]. The payback period depends on a wide range of factors such as utilised components, geographic conditions and government subsidies [10]. As mentioned earlier, profitability could be increased by designing multifunctional SHC systems. The payback period of all types of solar cooling systems falls within the range of 7.6-11.4 years [1], while in case of coupling solar cooling with heating (SHC), payback period is evaluated to be in the range of 3-15 years [10]. PV-based SHC systems face additional barrier restraining their development, e.g. high price of battery storage required for continuous operation of the system over the periods of scarce solar energy. On the other hand, capital cost of photovoltaic solar panels is decreasing and that trend contributes to more favourable financial metrics [1].

Cooling with absorption chillers is well-established technology that has been widely used in air-conditioning but up till now absorption cycles have been driven mainly with natural gas or industrial waste heat [1]. Studies indicate that currently large-scale SHC absorption chillers are not competitive compared to conventional cooling, leaving aside government subsidies [1, 9]. That applies especially to the buildings with limited area exposed to solar radiation. Nevertheless, SHC absorption chillers are expected to become a promising solution in addressing environmental issues [9] but special attention must be paid to improving their economical performance [1]. Among various SHC systems, absorption chillers technology is the most developed commercially [5] and therefore considered to compete with conventional air-conditioning in foreseeable future [1].

### 1.3 Solar absorption chillers

Most common SHC systems shall consist of absorption chiller combined with solar thermal collectors and thermal storage system [7]. For reference, about 59% of SHC in Europe were based on absorption cooling technology in 2007 [5]. In research particular attention has been paid to the systems based on single-effect chillers coupled with low-temperature solar thermal collectors [1] and such attention corresponds to the most popular layout of solar

absorption chillers worldwide [10]. Subject of using high-temperature solar thermal collectors and multi-effect chillers in SHC gained less attention [1] and generally those systems are less widespread among the world. From that overview the following picture of the regular SHC system emerges: such a system is based on thermally-driven single-effect absorption cooling cycle and consists of four basic components, namely an absorption chiller combined with a (low-temperature) solar thermal collector, a storage tank and an auxiliary heater. That typical system is usually multifunctional as it serves also for domestic heating and/or hot water production.

In comparison to conventional vapour compression chillers, absorption chiller is a device featuring such advantages as: quiet and low-vibration operation, little maintenance and environmental-friendly functioning [1, 11]. Additionally, device realises cycle in which pressure of medium in liquid state is to be increased and that could be done economically with a pump as opposed to a situation occurring in vapour compression cycle when a compressor must be applied to increase pressure of medium in gaseous state. Therefore absorption chiller requires little mechanical energy input [1]. In comparison to other SHC systems, absorption chillers achieve higher COP than adsorption chillers [7].

### 1.4 Solar absorption chillers operating on NH<sub>3</sub>-H<sub>2</sub>O mixture

Performance of absorption chiller (AC) depends on properties of operating mixture consisting of refrigerant and absorbent. Two fluids must comply with a wide range of requirements. Their liquid phases must be miscible in all temperatures reached in cooling cycle [1]. In such a range of temperature, fluids and their mixture should be chemically stable, non-toxic and non-explosive. [1,12]. Another favourable property is possibly large difference between the boiling points of mixture and pure refrigerant [12]. Otherwise applying dephlegmator may be needed [1]. High heat of vaporization and capacity to reach high concentration within the absorbent is also considered as advantageous refrigerant property since it allows to realise cooling process with low circulation rate [12]. While reaching high concentration of refrigerant in absorbent is beneficial, increasing ammonia initial concentration in mixture could decrease mass transfer rate and even stop the absorption process for ammonia initial concentration of about 60% [8]. Non-corrosive, inexpensive and safe for environment fluid pairs are preferred [12]. Refrigerant should be volatile in order to enable easy separation in generator [1], while absorbent ought to be non-volatile so rectification of absorbent will not be necessary after desorption [13].

Most prevalently used refrigerant-absorbent pairs are H<sub>2</sub>O-LiBr and NH<sub>3</sub>-H<sub>2</sub>O [1]. As ammonia freezing point in considered range of pressure is equal to -77°C, ACs utilising NH<sub>3</sub>-H<sub>2</sub>O are able to produce cooling

temperature below 0°C [12] but they need higher temperatures in generators than H<sub>2</sub>O-LiBr-based machines [1]. They also achieve lower COP [1] in a range of 0.5-0.6 [6], while corresponding values for H<sub>2</sub>O-LiBr are 0.7-0.8. Due to their capability to achieve temperatures below 0°C, NH<sub>3</sub>-H<sub>2</sub>O ACs are preferred for cooling, while H<sub>2</sub>O-LiBr ACs for air-conditioning [1]. H<sub>2</sub>O-LiBr displays some corrosive properties thus addition of anti-corrosives is required [6].

Despite slightly lower COP and higher driving temperature required in case of NH<sub>3</sub>-H<sub>2</sub>O ACs, they are free of some construction constraints present for H<sub>2</sub>O-LiBr ACs. The second fluid pair cannot operate in temperatures lower than 0°C due to water being refrigerant which freezes in such temperature but also temperature of 40°C cannot be exceeded because the possibility of LiBr crystallisation from mixture occurs as the saturation point is achieved [3]. Crystallisation could also occur when solution rich in LiBr salt has high concentration. Crystallisation may lead to blocking of the pipes and valves [1] therefore operational temperature range is restrained and that could limit utilisation of H<sub>2</sub>O-LiBr ACs in extreme weather conditions [1]. When it comes to physical size of the system, H<sub>2</sub>O-LiBr ACs are generally larger than their NH<sub>3</sub>-H<sub>2</sub>O counterparts, because vapour volume of refrigerant is significantly larger [6]. Since the difference between the boiling temperature of ammonia and water is not very high, NH<sub>3</sub>-H<sub>2</sub>O absorption chillers also need a dephlegmator to separate ammonia and water vapour inside the generator [1].

### 1.5 Multiple-effect cycles for solar absorption chillers

Another critical parameter affecting performance of ACs is number of times heat has been recycled before completing the loop. Single-, double- and triple-effect (alternatively: single-, double-, triple-stage) ACs could be listed as commercially available [1]. Number of effects corresponds to number of generators in which heat flow is harvested to realise the process of desorption. Higher COP could be achieved with increasing number of cycles but that operation requires higher temperatures for every further cycle [1].

It is reported that in regions characterised by low solar resources, solar multi-effect chillers are relatively inefficient thus single-effect is preferred choice [1]. Single-effect ACs' COP is limited to around 0.7 [13] and they require driving temperature of 80-100°C (LiBr) [13]. In order to raise COP of single-effect ACs, solution heat exchangers are applied for preheating solution entering the generator with heat received from water returning to absorber [1].

Double-effect ACs utilise additional generator and operate between different pressure levels. They achieve higher COPs (up to 1.4) but require higher driving temperature [1]. Starting with double-stage chillers, generators could be connected in different ways through series, parallel and reverse-series flow cycles [1] displaying non-obvious dependence between layout structure and performance of a chiller [1]. Currently all commercially

available double-effect ACs operate on H<sub>2</sub>O-LiBr cycle since NH<sub>3</sub>-H<sub>2</sub>O requires higher pressure.

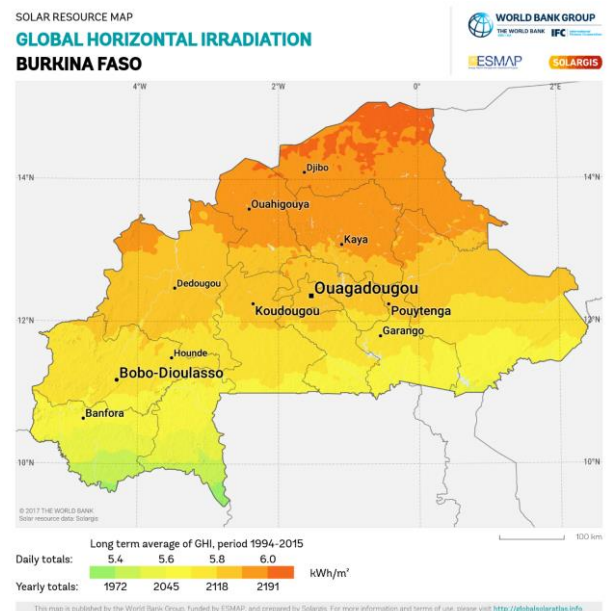
Studies have shown that variable effect (1.n-effect) absorption cycles are under development. Such systems allow vapour to undergo either single- or double-effect cycle and ratio of both vapour volumes subjected to those cycles is regulated by generators temperatures [10]. As no specific components differ 1.n-effect cycle from single-effect cycle, [10] it could easily extend a range of ACs utilisation.

Three-effect configuration rarely occurs because driving temperature must be higher than in case of single- and double-effect ACs. There are some hybrid configurations in which single-effect cycle powered with solar thermal energy is used accompanied by double-stage gas-fired cycle. Those different methods could work independently or simultaneously [10].

## 2 Analyses

### 2.1. Energy sources

The analyses were undertaken for Ouagadougou which is the capital of Burkina Faso. Burkina Faso is an African country classified as one of the Third World Countries. Its electrification rate is estimated to be around 20%, meaning that more than 12.1 million people do not have access to the electricity [14]. The solar-powered absorption refrigerator facilities could improve healthcare in power-deprived regions. Annual solar irradiance in Burkina Faso is equal to 19.8 MJ/m<sup>2</sup> per day and direct sunshine is available over 3000 hours per year [15].

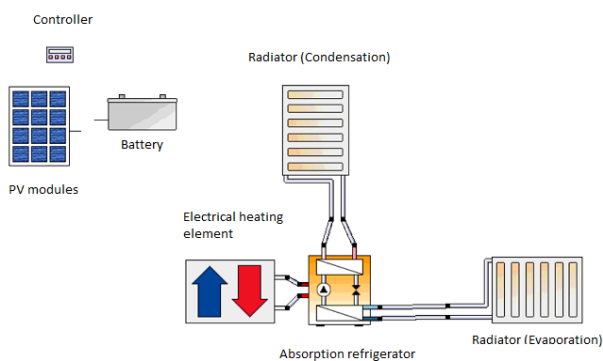


**Fig 1.** Solar power potential in Burkina Faso [16]

Fig 1. shows the map with average annual solar irradiance in the country. Annual mean global irradiation in Burkina Faso falls within the range of 5.4-6.0 kWh/m<sup>2</sup>, providing suitable conditions for use of photovoltaics. Solar refrigeration system could

become inexpensive and environment-friendly source of cooling for storage facilities. This paper describes an off-grid cold storage system which is able to keep medications cool for a long time. This installation may be cut off from external electrical network and powered with local sources of renewable energy.

## 2.2. Solar-powered absorption refrigeration cycle with circulation based on convection



**Fig. 2.** Schematic diagram of a solar-powered absorption refrigerator system

The main elements of cooling system are shown in Fig. 2 as following: PV modules, absorption refrigerator, two heat exchangers e.g. evaporator and condenser, battery storage, electrical heating element and the control system. The incident solar radiation is converted to electric current by three PV modules of combined power equal to 480 W. After regulating its electrical parameters the current is supplied to connected 12V battery with capacity of 200 Ah and to electrical heating element. Control system switches power supply to heating element if the temperature of working mixture ( $\text{NH}_3\text{-H}_2\text{O}$ ) is lower than  $80^\circ\text{C}$  or to the battery if this temperature is achieved. Ammonia absorption refrigerator produces cooling effect in order to maintain the low temperature in analysed  $90\text{dm}^3$  tank by boiling working mixture and forcing its circulation. Condensation, the subsequent step in the cooling process, is realised by rejection of latent heat to the ambient. The refrigerant enters the evaporator as a low-quality saturated mixture, and it completely evaporates by absorbing heat from the refrigerated space. All the flows in refrigerator are based on convection, caused by changes of density. Therefore in presented system electrical heating element is the only device consuming considerable amount of energy. COP of the analysed installation was calculated as a 0.55 which value is much lower than COP of systems based on vapour compression which is at the level of 3.5. There is a risk of ammonia leakage which is toxic to people but it is minimized by tight seal of the system.

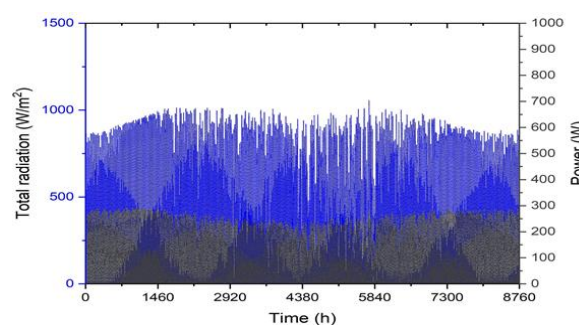
## 2.3. System simulation

Some critical parameters of the system were summarized in Table 1.

**Table 1.** System key parameters

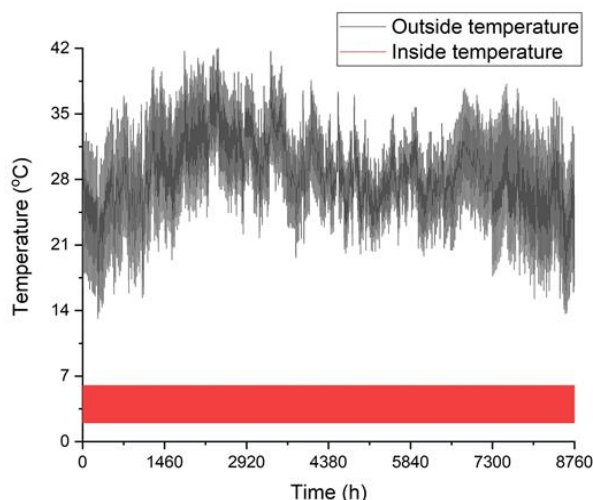
Description	Specification
Volume	$90\text{ dm}^3$
Cooling set point	$2\text{-}6^\circ\text{C}$
Operation hours	Continuous
Solar fraction	100%
PV panels power	480 W
Electrical heater power	250 W
COP	0.55
Weather data	Ouagadougou, Burkina Faso

Figure 3 shows solar panels' energy output in following time steps, depending on irradiation of the area. Simulation shows that the average annual energy production ensures work of solar refrigerator system cut off from external electrical network.



**Fig. 3.** PV panels power output depending on the received irradiation

The results were obtained through TRNSYS simulation which was run with 6 minutes time step. The analysed system has successfully maintained storage temperature below the point of  $6^\circ\text{C}$ , even while the ambient temperature was over  $40^\circ\text{C}$  during the peak of summer season (Fig. 4).



**Fig. 4.** Simulated internal temperature and ambient temperature over the period of one year

## 3 Conclusions



The considered cooling appliance powered by three PV modules with nominal power of 480 W is sufficient to accumulate energy for continuous cooling and keeping medications in safe conditions off-grid. It is possible to maintain the temperature within the range of 2-6°C regardless of the season. Absorption cooling system has wide range of applications in many branches of industry. Africa's climate shall provide huge potential for use of solar-powered cooling systems. Considering the profitability of analysed device, proposed system allows to save **2.19** MWh per year, which corresponds to about 280 €. Construction of the device costs more or less 1500 €, which means that SPBT (simple payback time) is below 5.5 years. Lifetime of the installation is limited by lifetime of the battery storage, which is declared by the producer to be around 10 years. There are possibilities of upgrading the system, for example with the use of solar tracking for PV modules and accumulation of heat in PCM or water tank.

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