Project

by the Federal University of Rio de Janeiro
in cooperation with the Beuth University of Applied Sciences in Berlin
in the field of Building Services and Energy Management

Technical and Economic Assessment of the Integration of Refrigeration Concepts into the proceeding Extension of Solar Energy Systems in Brazil

Prof. D. Sc. Giovani Manso Ávila
Prof. Dipl.-Ing Katja Biek

Christopher Wiencke
An der Feisneck 14b
17192 Waren (Müritz)
christopher.wiencke@poli.ufrj.br
DRE: 115211837

Rio de Janeiro
September 2016

Index

1 Introduction 1

2 Technical Overview 4

2.1 Solar Energy 6

2.1.1 Solar Thermal Collector 7

2.1.2 Photovoltaic 11

2.2 Cooling Systems 13

2.2.1 Absorption Chiller 16

2.2.2 Conventional Compression Chiller 19

3 Case Study 20

3.1 Inventory Analysis 21

3.1.1 Climate and Location 21

3.1.2 Architecture 22

3.1.3 Building Services 22

3.1.4 Conclusions and Measures 24

3.2 Simulation and Design 28

3.2.1 The thermal Load 28

3.2.2 Selection and Design of the Equipment 34

3.2.3 Economic Assessment 37

3.2.4 Environmental Benefits 37

4 Conclusion 38

5 References 40

6 Appendix 41

1 Introduction

In wide parts of our planet is a lot of electrical energy used for refrigeration technique to accomplish a comfortable environment and also to cool necessary machines, which were surrounding us. Global warming, desertification and the expanding of the tropic belt causing a high raising demand of cold worldwide.

The use of solar-assisted air-conditioning is very meaningful, especially in warm, subtropical regions with a high solar radiation. In this connection the radiation rate is extensive according to the refrigeration demand.

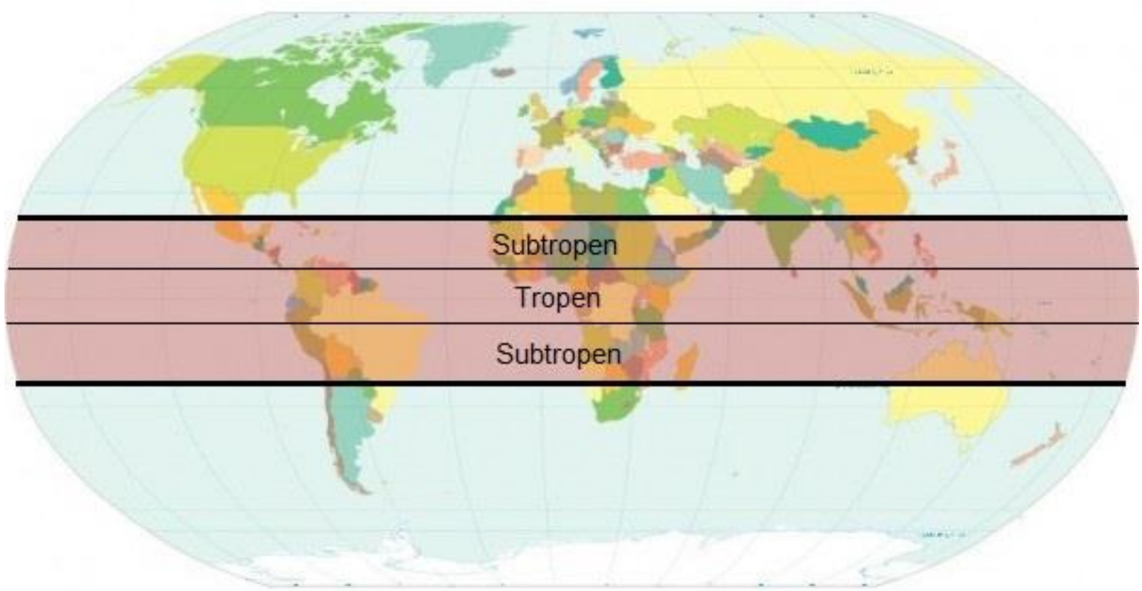


Figure 1 Tropic Belt

The solar cooling provides a significant potential of an electrical energy reduction for air-conditioning in buildings, arranges fossil fuel savings and decreases peak demands of electrical energy.

Furthermore solar cooling decreases the ecological footprint of tropical cities due to achieving carbon emission reduction and using environmental friendly refrigerants. The solar array yields thermal load reduction of the building. Last but not least it impacts in a positive way the urban microclimate through absorbing the solar irradiation on the roof.


Figure 2 - Thermal Solar Array and Figure 3 Split Coolers with Compressor Operation

The intention of this project is to analyze which factors have an influence in the adequate selection of system components of a solar-assisted cooling system for an energy efficient refrigeration of buildings. This paper contains the most important processes for solar-assisted cold generation and is organized into the following main chapters:

The second chapter comments on the current state of the art in the field of solar cooling. Different technologies in terms of varying climatic conditions are critically probed. The section describes the fundamental aspects and components of solar-assisted air-conditioning in buildings, the function and the benefits. It includes also non-thermally driven applications like conventional electricity driven vapor compression chillers and a photovoltaic driven compression cycle. Summarized it gives the reader an overview of the latest scientific knowledge.

In chapter three there will be a comparison of the different cooling systems overworked. Based on an energetic building analysis of an existing elementary school in Rio de Janeiro is shown in which way solar-assisted air-conditioning is an energy efficient alternative to conventional electrical driven compressor systems.

Therefore the solar coverage ratio will be calculated by using the software HVAC Load for the investigation of the cooling load.

The calculated cooling demand gives the basis for the design of different refrigeration systems by using solar energy. A list of the necessary devices, the estimated installation and the calculated operation costs will give the requirement for an ecological and economic assessment and the repayment of the investment.

The fourth chapter demonstrates the achieved results and presents the conclusions.

In this context the following questions will be merged and answered in the course of this work:

- Which techniques can be used and obtained?
- Which is the most efficient system for the respective requirements?
- What is the correlation between solar gain and cooling demand?
- Which solar arrays provide the highest cost-efficiency?
- How to reduce the refrigeration demand hence the cooling capacity and investment costs of solar cooling system?
- Which auxiliary energy can be installed and what is the selection criterion?
- Can solar-assisted cooling systems compete economically against conventional compressor controlled systems?

2 Technical Overview

This chapter describes the function of solar-assisted refrigeration in buildings. Different technical terms, operation parameters, different concepts and their application scopes will be presented. The following survey of the technical standard serves the fundament for the selection of technology and their suitable components regarding the mentioned primary school in Rio de Janeiro.

Before presenting the solar cooling technology status, it is important to define the technology currently on the market and under development. Solar energy can be converted into cooling using two main principles

1.) Heat generated with solar thermal collectors can be converted into cooling using thermally driven refrigeration or air-conditioning technologies. Most of these systems employ the physical phenomena of sorption in either a closed thermodynamic cycle or an open system (2.2 Cooling Systems).

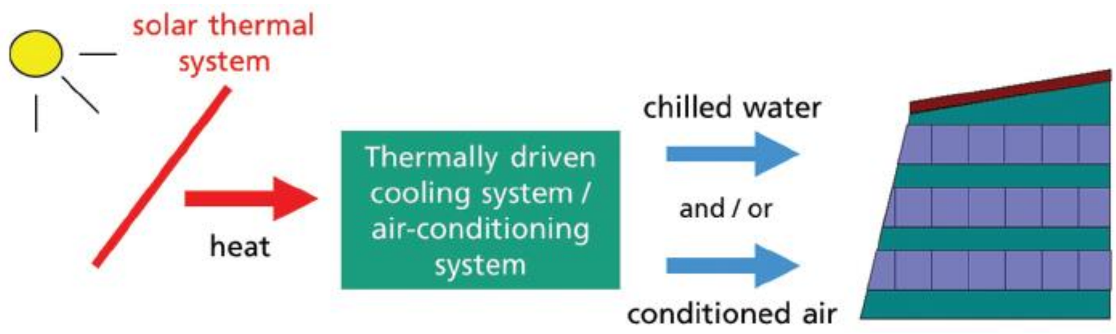


Figure 4 - Simplified Scheme the thermally driven cooling process [1]

2.) Electricity generated with photovoltaic modules can be converted into cooling using common technologies that are mainly based on vapor compression cycles (PV Cooling)

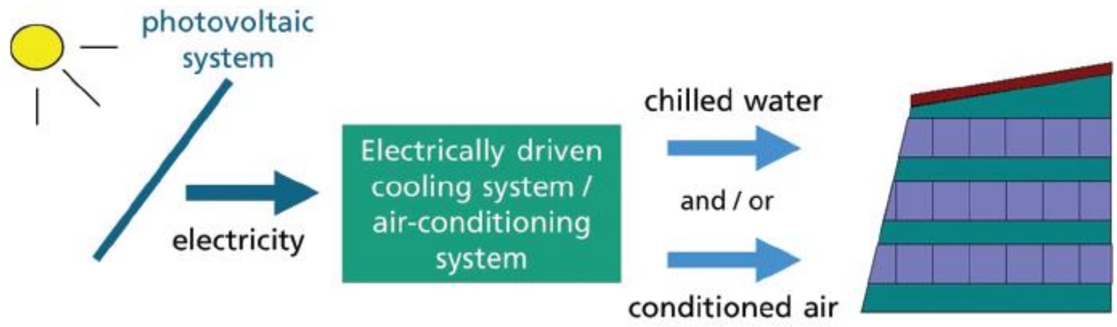


Figure 5 - Simplified Scheme of the electrically driven cooling process [1]

The first principle – solar thermally driven cooling – is mainly applied for comfort cooling and air-conditioning in buildings and first pilot installations that have been realized for large capacity refrigeration applications.

The second principle – solar electricity driven cooling (PV Cooling) – is not commercially widespread and mainly used now for solar driven refrigerators for cooling medicine in remote, sunny regions. [2]

The Brazilian Electricity Regulation Agency (ANEEL- Agência Nacional de Energia Elétrica) legislated a law, which obligates the local energy provider to inject private generated electrical energy from residential microgeneration systems, e.g. photovoltaic into the public grid. Due to this fact, a high extension of solar energy utilization is expected.

In 2015, the creation of a new fund was announced, with a capital of USD 9.7 billion12 from public and private contributions, to finance electricity generation in the Northeast region, including 8 GW of wind and solar power [3].

2.1 Solar Energy

Brazil receives solar energy in the order of 10^13 MWh per year, which is about 50.000 times the country's annual consumption of electricity. The country has an average solar radiation of 5 kWh/(m^2 day) and a cooling demand up to 200 W/m^2. In Europe, where the most solar cooling systems are in operation, the average solar radiation is around 3 kWh/m^2/day and the cooling demand is only 40..70 W/m^2.These facts show the good conditions for solar cooling applications in Brazil. [4]

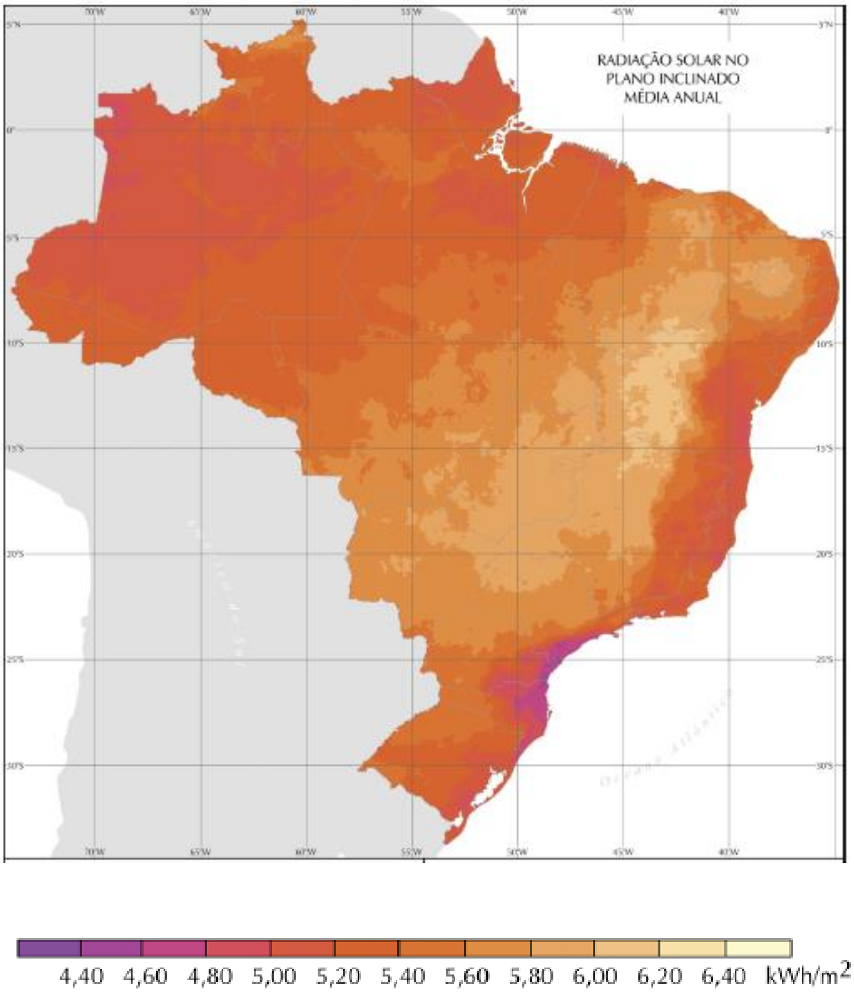


Figure 6 Annual average solar irradiance in Brazil [2]

2.1.1 Solar Thermal Collector

In Brazil a broad variety of solar thermal collectors is available on the market and many of them are applicable in solar cooling and air-conditioning systems. However, the appropriate type of the collector depends on the selected cooling technology and on the site conditions, i.e., on the radiation availability.

General types of stationary collectors are shown in Figure 7, construction principles of improved flat-plate collectors and evacuated tube collectors are given in Figure 8.

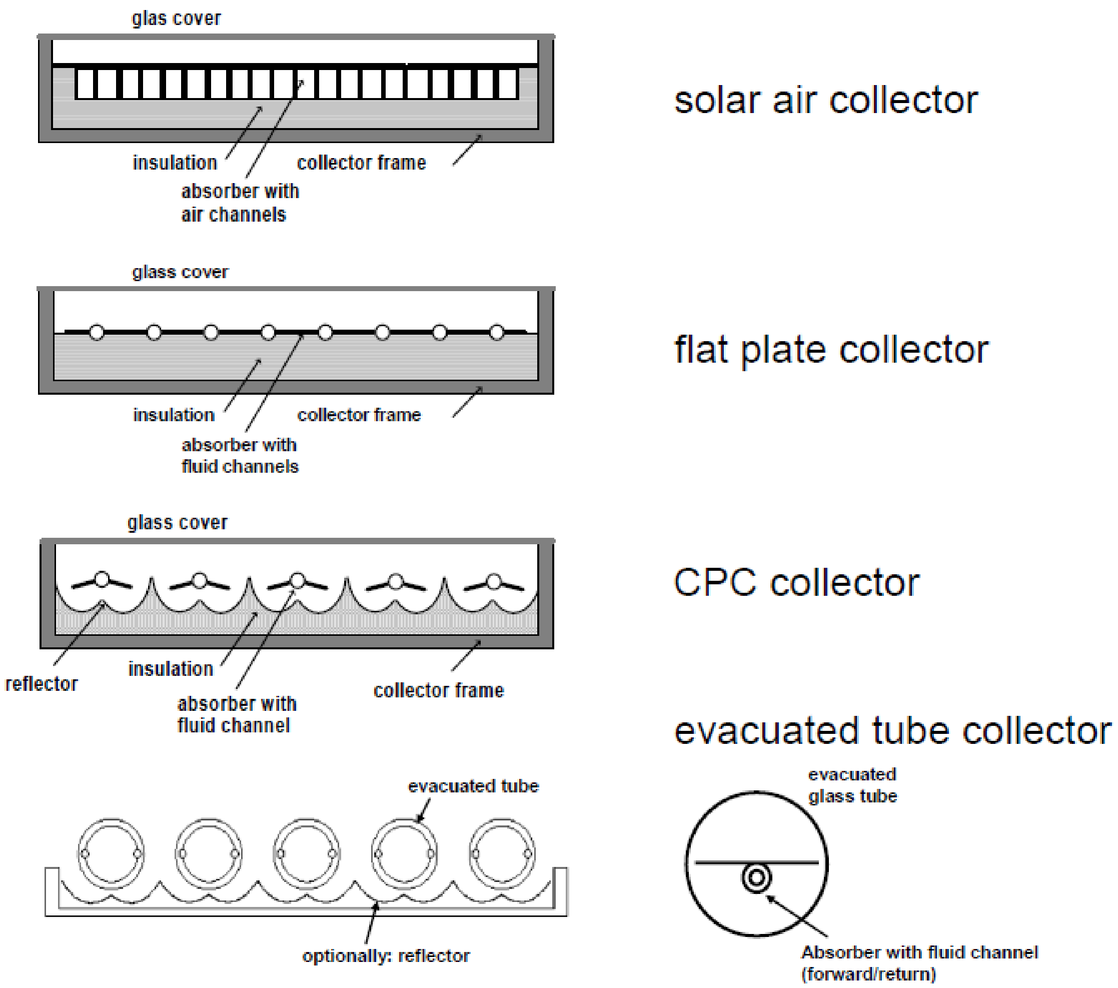


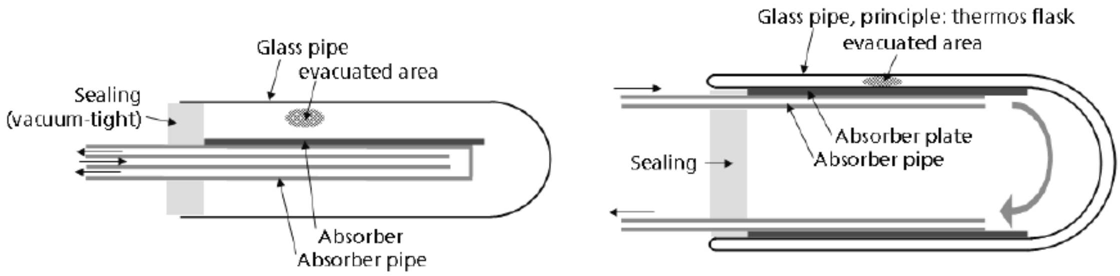
Figure 7 Examples of stationary collectors, applicable for solar cooling [1]

The flat-plate collector is applicable with good results in the temperature range up to 90°C. The heat losses are minimized through improved insulation and an additional convection barrier (Teflon foil) between glass cover and absorber. Source: S.O.L.I.D. Other manufacturers use a second glass cover and/or antireflective coatings.

The use of cost-effective solar air collectors in flat plate construction is limited to desiccant cooling systems, since this technology requires the lowest driving temperatures (starting from approx. 50°C) and allows under special conditions the operation without thermal storage. To operate thermally driven chillers with solar heat, at least flat plate collectors of high quality (selective coating, improved insulation, high stagnation safety) are to be applied. [4]

Figure 8 shows two principles of evacuated tube collectors. On the left, the 'classical' principle is shown, demanding for a vacuum tight sealing. On the right, the thermos flask principle is shown. Source: ISE. Bottom: application of the heat-pipe principle. The pipe is freeze protected and stagnation safe (but not the collecting pipe).This collector type usually has the highest cost of evacuated tube collectors. [5]

A wide range of concepts for evacuated tube collectors exists, e.g., collectors with direct flow of the collector fluid through the absorber pipe, or with a heat pipes in the tube. Also, the glass tube may either follow the traditional principle of a tube, sealed on both ends, or may follow the thermos flask principle. [5]



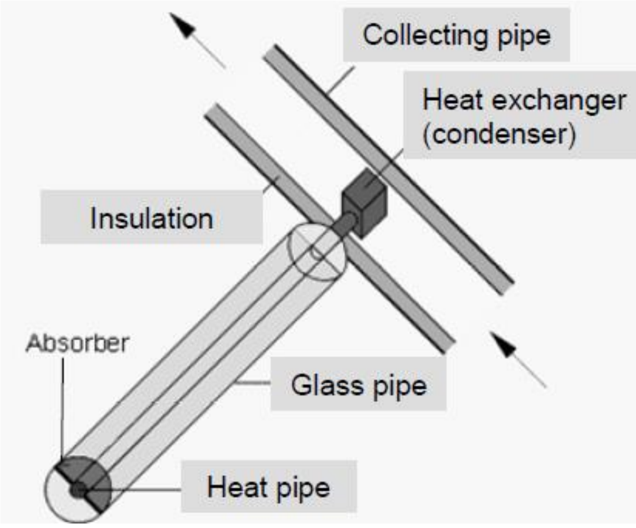


Figure 8 Different constructions of evacuated tube collectors [1]

Table 1 shows the characteristics and costs available on the Brazilian market for solar-assisted air-conditioning applications and useful collectors.

Collector Type	Evacuated tube	stationary CPC* (without vacuum)	Flat-plate (selective coating)	Flat-plate (selective coating)
Supplier	Apricus Solar Co., Ltd/ Fibratec	AO SOL, Lda	BOSCH GmbH	Cumulus S.A. Ind. Com.
Model	AP-30	CPC AO SOL 1.5	Bruderus Logasol SKN 3.0	CSC Premium 200
Aperture area of a single module [m²]	2,82	2,38	2,256	-|
Gross area of a single module [m²]	4,14	2,69	2,398	1,95
Price of a single module [R$]	4081 Source: Fibratec Unasol Energias Renováveis Brazil		1050,28 Source: Bosch Brazil	1148 Source: Quali Tek Aquecedores, Rio de Janeiro
η_0 conversion factor [-]	0,656 (aperture area)	0,628 (aperture area)	0,770 (aperture area)	0,755** (gross area)
a_1 heat transfer coefficient [W/(m²K)]	2,063 (aperture area)	1,47 (aperture area)	3,681 (aperture area)	4,717** (gross area)
a_2 Temperature depending heat transfer coefficient [W/(m²K²)]	0,006 (aperture area)	0,0220 (aperture area)	0,0173 (aperture area)	not available**
η (ΔT=60K and G=500W/m²)	0,37	0,29	0,32	0,19 Equation 2.6
η (ΔT=60K and G=1000 W/m²)	0,51	0,46	0,55	0,47 Equation 2.6
Specific costs €/m² (R$/m²) area referred to the collector gross area.	985,75 R$/m²	223 €/m² (conversion factor 2.7 R$/€) 602,1 R$/m²	437,98 R$/m²	574 R$/m²

* Source of the data [6].
** According GREEN Solar PUC-Minas (Prof. Elizabeth Duarte Pereira) the a2-value of the Cumulus CSC Premium 200 Collector is negative. The INMETRO/PROCEL test procedure the efficiency values are referring to the gross area of the collectors.

Table 1 Characteristic values and cost of solar collector typologies [4] (modified)

2.1.2 Photovoltaic

A photovoltaic system or solar PV system is a power system designed to supply usable solar power by means of photovoltaics. It consists of an arrangement of several components, including solar panels to absorb and directly convert sunlight into electricity, a solar inverter to change the electric current from DC to AC, as well as mounting, cabling and other electrical accessories. PV systems range from small, roof-top mounted or building-integrated systems with capacities from a few to several tens of kilowatts, to large utility-scale power stations of hundreds of megawatts. Nowadays, most PV systems are grid-connected, while stand-alone systems only account for a small portion of the market [7].

There is the possibility to run a conventional air-conditioning system by a photovoltaic system (PV). Two technical solutions can be realized:

- A grid connected PV system generates independently on an annual average a certain amount of the energy, consumed by the compression chiller. At the moment the specific investment cost for 1 kW is around 3000 €. This match the specific investment of 1 kW solar thermally generated cooling power. This is only the investment for the considered material; the installation cost of a PV system is lower, because there is no need of piping. But, there is no electricity feed in regulation for PV generated energy in Brazil.

- The PV system is direct connected to the compression chiller, thus it can run without any grid connection. As yet there are only applications in small capacity ranges, e.g. food or medicine storages, since special components are necessary for this direct coupling. There exists no data base of the investment costs, but there are probably equal or higher than for small solar thermal driven cooling application. [4]

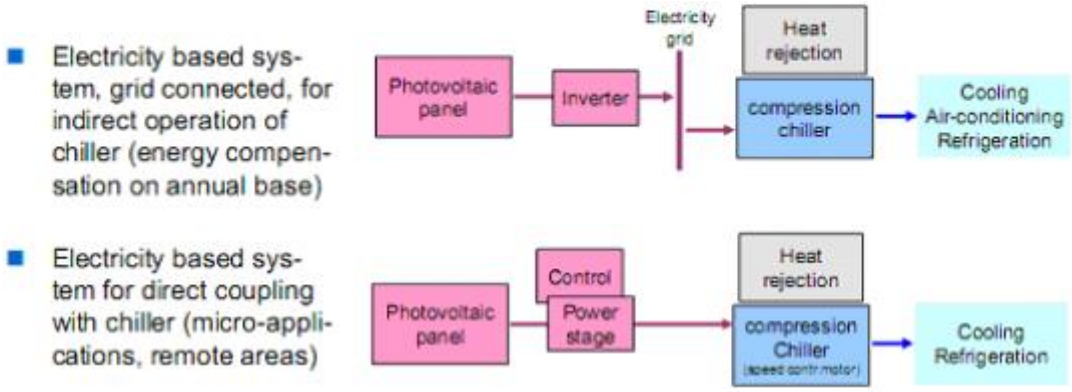


Figure 9 - Solar cooling possibilities with PV systems [1]

It is important to note that the solar collector field has options more or less the same size. The next figure shows a comparison between a PV direct coupling system and solar thermal driven system, indicating the COP and efficiency of each system. Finally, solar thermally driven COP´s in the order of 0.28, compared to 0.3 photovoltaic panel system / vapor compression. It must be mentioned here that the COP of solar/sorption system can be increased by using a collector with a higher efficiency, for example some special types of evacuated tube collectors have an efficiency of maximum 60% at 90°C water temperature. Normal flat-plate collectors with selective coating have efficiency at this temperature level of only 40%. [4]

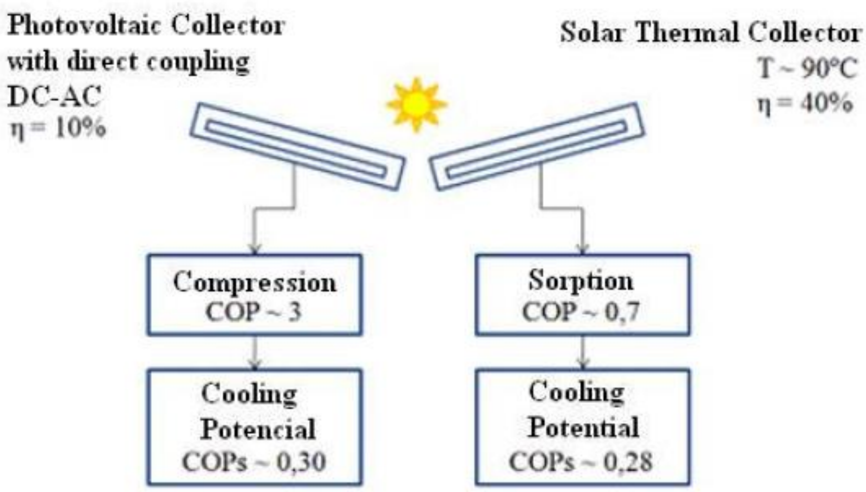


Figure 10 - Comparison of COP´s and efficiency between a PV direct coupling system and a solar thermal driven system [8]

2.2 Cooling Systems

Solar cooling technology uses heat in a thermally driven cooling process. Within solar cooling, there are two main processes:

- Closed cycles, where thermally driven sorption chillers produce chilled water for use in space conditioning equipment (air handling units, fan-coils, chilled beams, etc.).

- Open cycles, also referred to as desiccant evaporative cooling systems (DEC), typically use water as the refrigerant and a desiccant as the sorbent for direct treatment of air in a ventilation system.

For closed cycle systems, two types of sorption processes exist: adsorption and absorption based systems. Based on closed cycle sorption; the basic physical process underpinning both technologies consists of at least two chemical components, one of them serving as the refrigerant and the other as the sorbent. The efficiency of closed cycle systems can vary depending on the driving temperature.

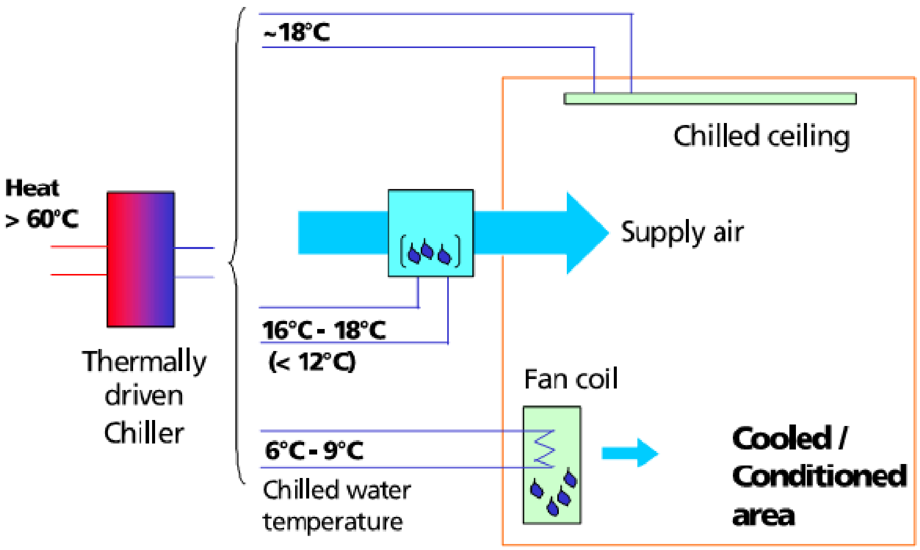


Figure 11 - Closed cycle system - chiller water is produced and transferred to the decentralized units like fan-coils, chilled ceiling or AHU [1]

While closed cycle systems produce chilled water, which can be supplied to any type of air-conditioning equipment, open cooling cycles produce conditioned air directly. Thermally driven open cooling cycles are based on a combination of evaporative cooling and air dehumidification by a desiccant (i.e. a hygroscopic, moisture absorbing material). In general, desiccant cooling systems are an option with centralized ventilation systems, offering the ability to pre-treat air entering a conditioned space.

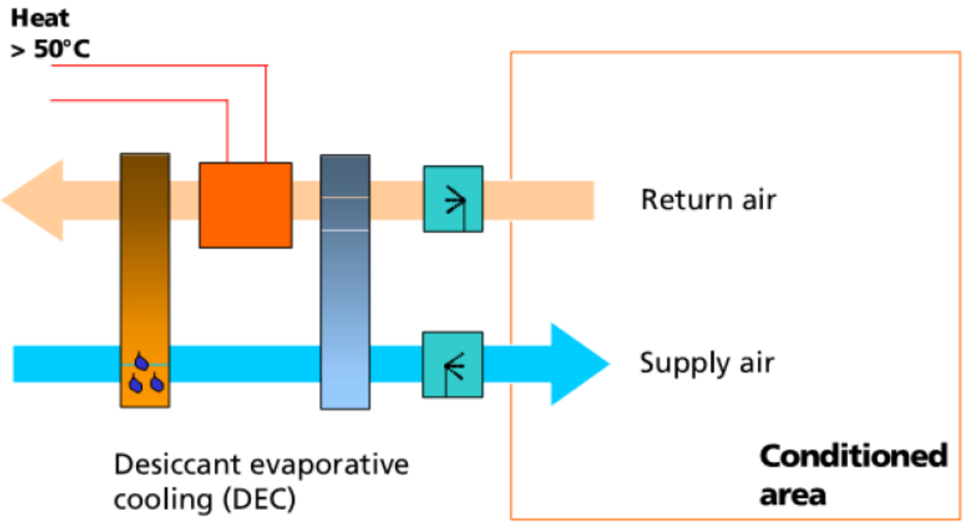


Figure 12 - Open sorption cycle: Supply air is directly cooled and dehumidified in an air handling unit (AHU) [9]

Solar cooling has a number of attractive features compared with its alternatives. Since maximum solar radiation usually coincides with peak cooling demand, solar cooling can help reduce electrical network peaks associated with conventional cooling. If widely deployed, solar cooling will reduce the need for expensive additional electricity network resources associated with electrically powered cooling. Avoiding additional electricity transmission and distribution reinforcement driven by peak cooling loads can lead to substantial cost reductions. Moreover, solar thermal cooling can also deliver cooling in the evening when using thermal storage.

Outside the summer period, solar cooling systems can be used for other heating purposes such as domestic hot water preparation or space heating. Open cycle solar cooling offers humidity management as well as space cooling. Also solar thermal cooling, just as any other absorption chiller, does not use refrigerants (CFCs and HCFCs, used in electric compression chillers) which are harmful greenhouse gases. However, solar cooling is still in the early stages of market development; costs need to be reduced through further development and increased deployment. A standardized, effective and simplified range of technology arrangements require development – particularly for single-family and multi-family dwellings – to enable solar cooling to compete with conventional and supported renewable technologies and achieve widespread deployment. Quality assurance and system certification procedures are also needed to help stimulate the market by building buyer confidence [10].

Another type of technology which has chained increasing attention over the last 15 years is desiccant cooling technology (DEC). Using this technology, air is conditioned directly, i.e. cooled and dehumidified. Desiccant cooling systems exploit the potential of sorption materials, such as silica gel, for air dehumidification. In an open cooling cycle, this dehumidification effect is generally used for two purposes: to control the humidity of the ventilation air in air-handling units and if possible to reduce the supply temperature of ventilation air by evaporating cooling [6].

Both systems in principle have a contrary characteristic: cooling processes perform better with higher temperatures while lower temperatures are better for the collectors. As a result, if both technologies are chosen, an optimum operation temperature results from both characteristics [9].

2.2.1 Absorption Chiller

Absorption chillers use heat instead of mechanical energy to provide cooling. A thermal compression of the refrigerant is achieved by using a liquid refrigerant/sorbent solution and a heat source, thereby replacing the electric power consumption of a mechanical compressor.

For chilled water above 0°C, as it is used in air conditioning, a liquid H2O/LiBr solution is typically applied with water as a refrigerant. Most systems use an internal solution pump, but consume only little electric power.

The main components of absorption chillers are shown in the figure below:

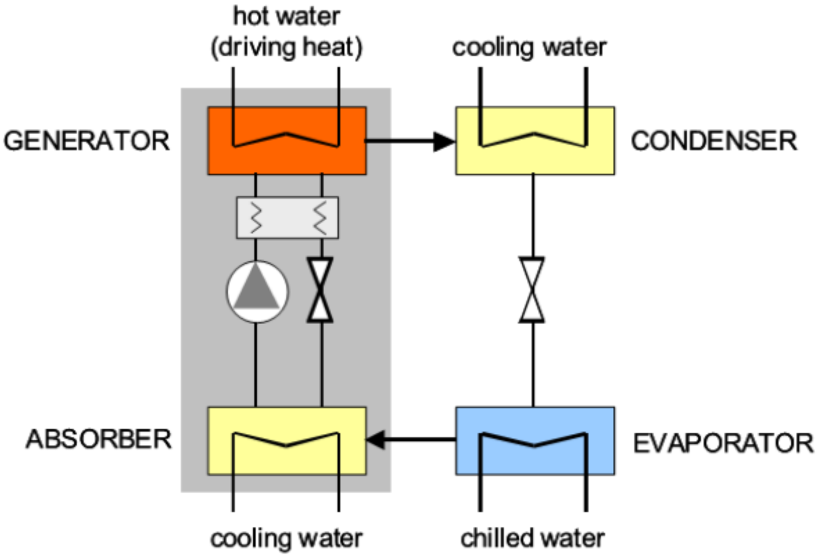


Figure 13 - Schematic drawing of an absorption chiller [1]

The thermal coefficient of performance (COPth) is the ratio of useful cold per unit of driving heat:

$$COP_{th} = \frac{useful\ cold}{driving\ heat} = \frac{Q_{Cold}}{Q_{drive}}$$

In the next two figures the thermal absorption cycle process is shown:

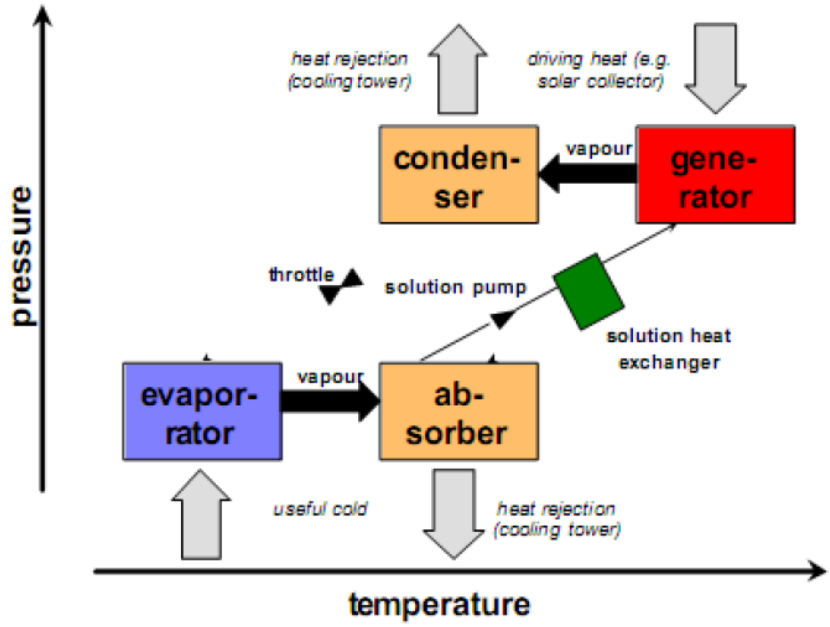


Figure 14 – Vapor pressure as a function of vapor temperature in an absorption cooling cycle process [1]

Absorption cycles are based on the fact that the boiling point of a mixture is higher than the corresponding boiling point of a pure liquid. A more detailed description of the absorption cycle includes the following steps [1].

1. The refrigerant evaporates in the evaporator, thereby extracting heat from a low-temperature heat source. This results in the useful cooling effect.

2. The refrigerant vapor flows from the evaporator to the absorber, where it is absorbed in a concentrated solution. Latent heat of condensation and mixing heat must be extracted by a cooling medium, so the absorber is usually water-cooled using a cooling tower to keep the process going.

3. The diluted solution is pumped to the components connected to the driving heat source (i.e. generator or desorber), where it is heated above its boiling temperature, so that refrigerant vapor is released at high pressure. The concentrated solution flows back to the absorber.

4. The desorbed refrigerant condenses in the condenser, whereby heat is rejected at an intermediate temperature level. The condenser is usually water-cooled using a cooling tower top reject the “waste heat”.

5. The pressure of the refrigerant condensate is reduced and the refrigerant flows to the evaporator through an expansion valve.

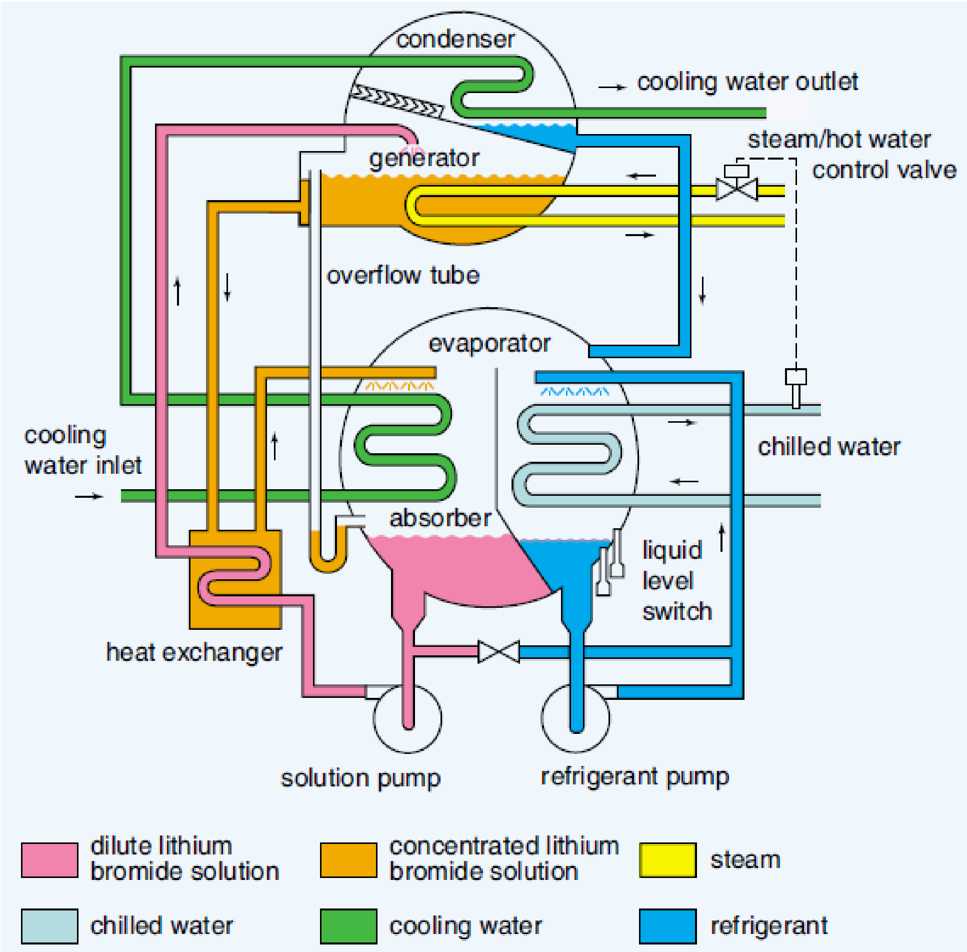


Figure 15 - Detailed function scheme of a single-effect absorption chiller “Carrier” [11]

The required heat source temperature is usually above 85°C and typical COP values are between 0.6 and 0.8. Until a few years ago, the smallest machine available was a Japanese product with a chilling capacity of 35 kW (10 TR). Recently the situation has improved due to a number of chiller products in the small and medium capacity range, which have entered the market. In general, they are designed to be operated with low driving temperatures and thus applicable for stationary solar collectors [7].

2.2.2 Conventional Compression Chiller

The most common refrigeration process applied in air-conditioning is the vapor compression cycle. Most of the cold production for air-conditioning of buildings is generated with this type of machine. The process employs a chemical refrigerant, e.g., R134a. A schematic drawing of the system is shown in Figure 16. In the evaporator, the refrigerant evaporates at a low temperature. The heat extracted from the external water supply is used to evaporate the refrigerant from the liquid to the gas phase. The external water is cooled down or – in other words – cooling power becomes available. The key component is the compressor, which compresses the refrigerant from a low pressure to a higher pressure (high temperature) in the condenser [10].

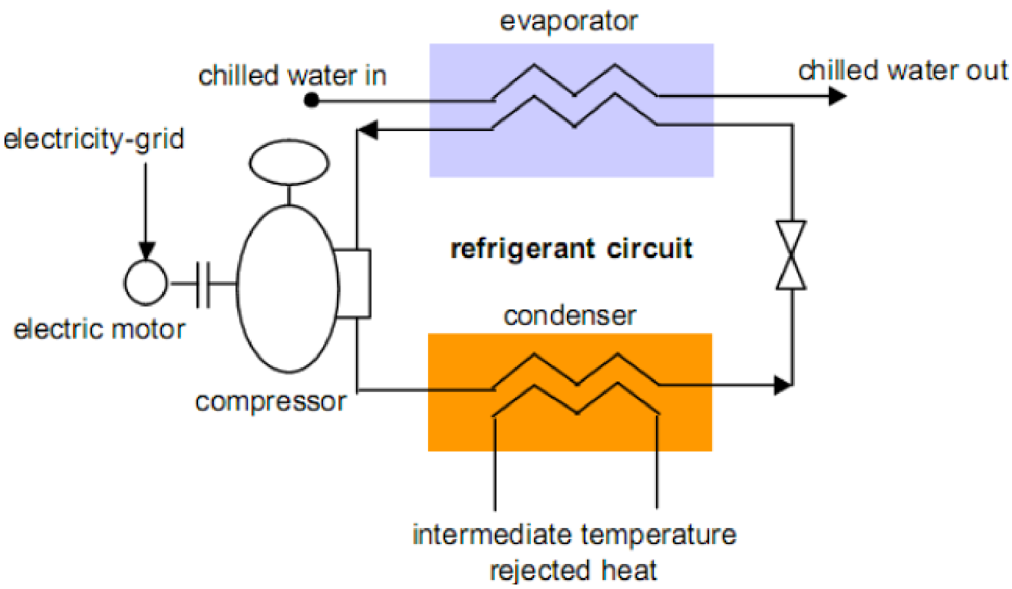


Figure 16 - Schematic drawing of a vapor compression chiller [6]

For a conventional, electrically driven vapor compression chiller, the COP is defined as follows:

$$COP = \frac{Q_c}{P_{el}}$$

Qc = cooling capacity [kW]

Pel = electric power input [kW]

3 Case Study

It’s intended to equip the rooms of an existing elementary school with a solar assisted air-conditioning system. The case study is used to provide the necessary theoretical base for the technical and economic assessment of the integration of alternative refrigeration concepts into solar energy systems.

The school “Escolinha Tia Percila” was founded in 1991 by the “Street Children Foundation” and, since then, helps families from Babilonia and Chapeu-Mangueira, by promoting social, cultural and educational development for the kids after school time. The “Street Children Foundation” is a Swedish organization formed in 1993 and since then it has been funding projects for underprivileged children in various parts of the world. The project is likely carried out within the association of “RevoluSolar”. Through collective voluntary work involving local electricians of the favela and the “Association of Inhabitants of Babilônia” in Rio de Janeiro, a group of inhabitants created “RevoluSolar”, a non-profit association aimed to inform and educate the local population about the social, economic and environmental benefits of solar energy. Also involved is the cooperation of the GIZ (German Corporation for International Cooperation). The GIZ Energy program in Brazil has the task of strengthening the role of renewable energy sources and efficiency.

As part of this project, “RevoluSolar” intends, as mentioned above, the implementation of solar cooling. The project will provide a clear demonstration character and will be accessible to the residents and all other visitors. The application of the project “Babilônia Solar” produces a high dissemination character and could attract the attention of other decision makers, planners, building services as well as the residents. A monitoring plan of Revolusolar will be created to collect the key performance parameters of the plant. The results and experiences of the project in the past are already conveyed to the Brazilian society through several interviews, publications in professional journals and lectures, events and specialist institutions.

3.1 Inventory Analysis

In the case of an existing building, first of all an inspection is necessary to collect relevant data and to prove structural and technical conditions. The building analysis gives information regarding the energy efficiency potential. Hot spots are going to be detected, which give the fundament to investigate possible modernization measures for reducing the electrical energy consumption.

3.1.1 Climate and Location

Rio has a tropical savanna climate that closely borders a tropical monsoon climate according to the Köppen climate classification, and is often characterized by long periods of heavy rain from December to March. In inland areas of the city, temperatures above 40 °C are common during the summer, though rarely for long periods, while maximum temperatures above 27 °C can occur on a monthly basis.

Month	Temperature [°C]	Humidity [%]	Pressure [mb]	Precipitation [mm]	Sunshinehours [h]
January	30,2	79	950,5	137,10	211,9
February	30,2	79	951,4	130,4	201,3
March	29,4	80	951,9	135,8	206,4
April	27,8	80	953,8	94,9	181
May	26,4	80	955,1	69,8	186,3
June	25,2	79	957,0	42,7	175,1
July	25,0	77	957,9	41,9	188,6
August	25,5	77	965,5	44,5	184,8
September	25,4	79	955,2	53,6	146,2
Oktober	26,0	80	952,6	86,5	152,1
November	27,4	79	951,5	97,8	168,5
Dezember	28,6	80	950,3	134,2	179,6
Average	**27,3**	**79,1**	**953,6**	**89,10**	**181,82**

Table 2 Climate data for Rio de Jabeiro [12]

Rio de Janeiro is located in south-eastern Brazil and has the following geographic coordinates: 22°48'43" south latitude and 45°11'40" W.

3.1.2 Architecture

The object consists of five levels and a roof terrace. A total of eleven rooms provide an effective area of 240 m^2 and the average ceiling height is 2.8 m. The main facade has a south-east direction and possesses a high window proportion.

The canteen and its kitchen are located in the first upper floor. Air transfer bricks are obstructed, thus becoming very useful due to the high thermal load of the heat convection during the meals. The hot air rises and is carried away because of thermal processes and possible wind loads from the sea coast.

Picture 1 Escolinha Tia Percilia (South-East Face) [13] and its canteen in the upper floor

3.1.3 Building Services

The necessary technical devices do more than provide shelter from heat and cold, or from sun and rain. They must also provide a safe and healthy environment in which people can live, work and study. The elementary school provides for example artificial lighting, ventilation and refrigeration and also drinking water supply, drainage and plumbing.

During the inventory analysis all electrical devices were detected and in the relevant subsections separated and listed. Using the particular product data sheets from the manufacturer the respective performances and specific energy consumptions were investigated. The year of manufacture and the actual device state also provides information about the building service energy efficiency.

In all four classrooms and in both offices, air-conditioning and partly ventilation systems are installed (Picture 2).

Picture 2 - Window Air Conditioner and Communication networks (left); Ventilation and illumination supplies (right)

A high electrical energy consumption ratio in the residential sector in Brazil is caused by warm water supplies (Diagram 1). Most of the showers include an electrical instant-on water heater with a high connected load. There are no showers installed in the elementary school. The diagram also shows that the highest percentage is caused by cooling applications.

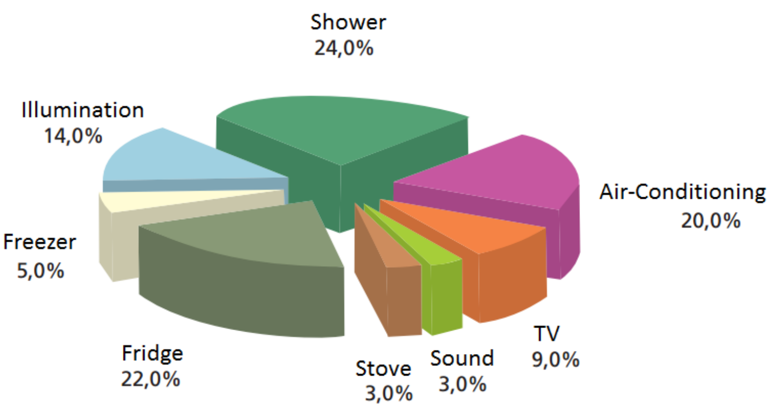


Diagram 1 – Participation of electrodomestics in the consumption of energy in Brazil [14]

The electrical power for the primary school is provided by the local energy distributor “Light”. Due to the last electricity bill the rate per kWh is 0.898 R$. By a summarized annual electrical energy consumption of 15.700 kWh, the total costs per year are about 14.000 R$. In Diagram 2 the monthly electrical energy consumptions are shown.

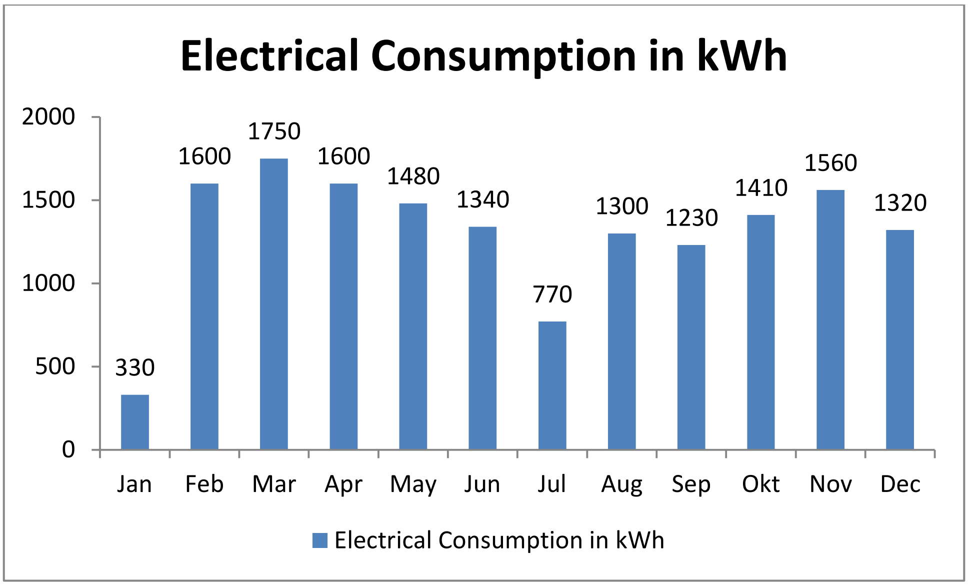


Diagram 2 – Monthly electrical consumption “Escolinha Tia Percila”

The variation of the electrical energy consumption is mostly influenced by the operation time and the climate. During January and half of July the school is out of service because of school vacations. The main consumption in these months is caused by freezers and refrigerators. During the winter the electrical consumption reduces because of lower temperature, hence a smaller refrigeration use is required.

3.1.4 Conclusions and Measures

The construction and other physical applications for windows, doors, steps, etc. are in a solid and safe state. The roof top area provides space and static requirements for solar thermal applications.

The absence of envelope insulation ensures a high change of air, fresh air and protects for entrapped moisture, but raise a high transmission heat loss, hence a greater cooling demand and energy consumption to achieve the requested interior temperatures.

Nevertheless, according to prior agreement with the client, insulation is not intended because there are no funds available and the regular school activities would be extremely affected.

For these reasons, in this work there will be no structural measures investigated, thus the energy consumption will be reduced by technical solutions.

Focusing on the building services, even for a layperson at first sight the conventional window air-conditioning units attract attention, because they are out of date. In Table 3 all air-conditioning units and their particular energy consumption are listed. Also the freezers and a couple of ventilation devices give cause for serious concern to change the situation. A high energy saving potential was found. Other technical application, for example the existing tubular fluorescent lamps and communication applications are in a good state.

Room	Marca	Modelo	COP (-)	Power (kW)*	Consumption (kWh)**	Service (h/m)***	Service (h)***	Consumption (kWh/month)
-2.1	Elgin	ERF30000	2.72	2.3	67.8	22.0	6	298
-1.1	Elgin	ERF30000	2.72	2.3	67.8	22.0	6	298
-1.2	Consul	CCO10B	3.02	0.7	20.4	22.0	6	90
0.1	Gree	GJE10AB	3.03	0.7	21.4	22.0	7	110
0.2	Elgin	ERF30000	2.72	2.3	67.8	22.0	6	298
2.1	Consul	CCM12D	3.08	0.8	23.9	22.0	7	123
Total								1217

* Technical data sheet of the manufacturer
** Investigated energy consumption "Procel" [15]
*** Operation time according to the local administration

Table 3- List of installed window air-conditioning units and their average monthly consumption

It is important to mention the user’s behavior in public buildings. An environmentally responsible behavior is rather unusual, especially in schools, where the everyday policy is often wasteful and unconscious. User interaction is very important and takes a big part regarding the building energy efficiency. Therefore all participants are needed to educate and inform about the terms and conditions.

To achieve a comfortable climate for everyone is a great challenge due to high density of people in a classroom. Thus, Brazilian norm (NBR 16401-3) exists to regulate the minimum air exchange and the fresh air supply. Often an expensive air duct system with an extensive hydraulic balancing is necessary to regulate the air distribution using ventilation flaps. Through the opening of just one window changes the pressure ratio in the network. The System will not deliver the minimum fresh air supply and works inefficiently at the same time. The likelihood that someone is ill at ease and wants to open a window is very big. In building sections or rooms in public buildings without windows a false user behavior is less affected and furthermore a construction like this statutory.

Due to high investment costs and installation efforts the air duct system will not be planned and won´t be considered during the further research. The air-conditioning component dimensioning is limited to the temperature and humidity condition in the building.

To provide sufficient oxygen the total volume of the room air must be exchanged with fresh air from the environment to avoid carbon dioxide, odor pollution and to reduce possible waste load. In this case the fresh air won´t be delivered through technical devices but through the users by opening the windows. Therefore to investigate the cooling load, a high air infiltration rate will be implicated (3.2.1 The thermal Load).

The canteen and the kitchen will not be be climatized by the planned cooling system due to the high infiltration ratio caused by the air transfer bricks. This area provides a ventilation system.

Diagram 3 shows the investigated percentage of the annual average participation of electro-domestics in the consumption of energy of the primary school. The air-conditioning systems have a percentage of 61%. Due to the mentioned electrical energy rates, the annual cost for air-conditioning is 8540 R$.

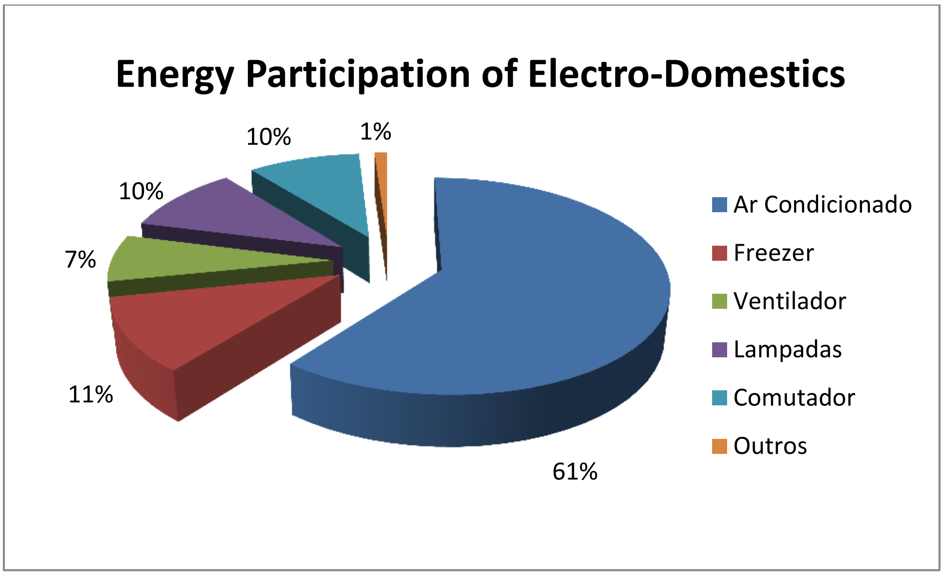


Diagram 3 - Percentage of the annual average participation of electro-domestics in the consumption of energy "Escolinha Tia Percilia"

3.2 Simulation and Design

3.2.1 The thermal Load

The following chapter shows the thermal building behavior. It gives information about the maximum cooling demand and how it changes due to climate variations during the hottest average day. According to the Brazilian norm for "Central and unitary air conditioning systems (NBR 16401) the thermal load will be calculated by using the building simulation program "HVAC Load Explorer".

First of all, the input data for the external and internal cooling load must be defined and added. The main influencing factors are shown in Figure 17.

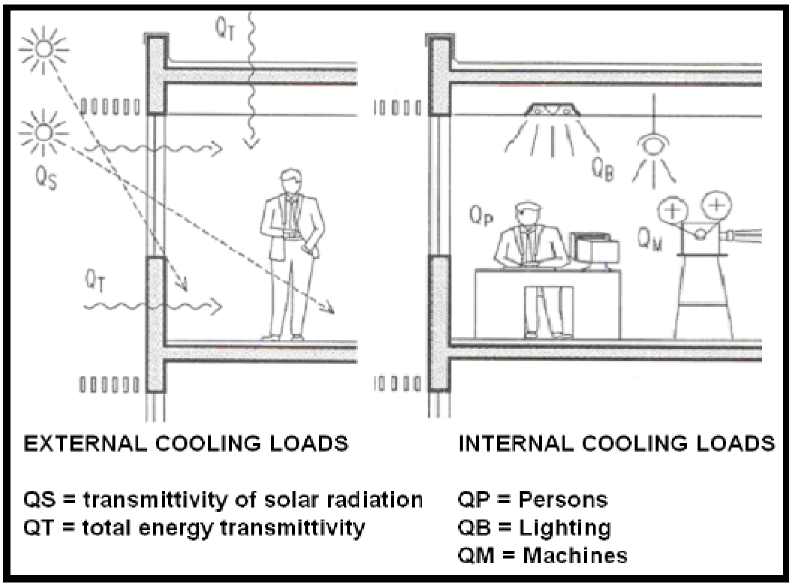


Figure 17 - External and internal cooling loads [16]

In Table 4 all relevant spaces with cooling demand are listed. The canteen and its kitchen are excluded. Due to the high infiltration rate there is no efficient cooling solution possible. The thermal load will be discharged as much as possible by using the existing ventilation system.

No.	Quarto	a (m)	b (m)	h (m)	A (m^2)	V (m^3)
-2.1	Classroom	6	6	2.4	36.0	86.4
-1.1	Classroom	6	6	2.9	36.0	104.4
-1.2	Classroom	4.4	6	2.9	26.4	76.6
0.1	Office	4.4	3.3	2.85	14.5	41.4
0.2	Computer	5.7	6	2.85	34.2	97.5
2.1	Office	4.3	6	2.7	25.8	69.7

Table 4 - Relevant spaces for the cooling load calculation

Table 5 presents the information retrieved for the case of 0.4% of the days not attended which is the worst possible average case.

Latitude	29,69S
Longitude	43,17W
Altitude	50 m
Pressure	101,22 KPa
Average Wind Velocity	4,8 m/s
Wind Direction	150° (0°North, 90° West)
Dry-Bulb Temperature	37, 3°C
Wet-Bulb Temperature	25,4°C
Relative Humidity	79%

Table 5 - Meteorological data input "Escolinha Tia Percila", Rio de Janeiro [9]

3.2.1.1 Building Data

According to the architect plans, the pretended area has a total floor space of 170m^2 and an average ceiling height of 2.76 m. The school has 5 floors encased by external walls with a thermal transmittance factor of 1,8W/(m^2*K) and windows with a 2,7W/(m^2*K). The windows are obstructed in the north direction, curtains are not provided.

Layer Name	Sp Heat(Btu/[lb.F])	onductivity(Btu.in/[hr.ft^2.F	Thickness(in)	Density(lb/ft^3)
Plaster	0.64	0.24	0.050	124.9
Brick	0.52	0.22	0.120	99.9
Plaster	0.64	0.24	0.050	124.9

Table 6 - Screenshot "HvacLoadExplorer" - Exterior wall layers

It must be mentioned that the energy transmissivity of the ground floor and roof bases possess a steady soil temperature of 20°C. The roof will be almost completely covered by the collector panels and required equipment, thus providing shade. Beside the roof shadowing, the building is partly shaded by a tree.

The hygienic air change rate is 30 m^3/h per person, 110 students relate to 3300 m^3/h. With a total volume of 469 m^3 in the pretended spaces the hygienic air change rate is 7.0 1/h. The fresh air will not be delivered through technical devices, but through the users by opening the windows. Thus, the investigation of the cooling load of the air infiltration rate will be implicated according to present climate conditions.

Regarding the internal load it is also important to determine the operation times of the different effective spaces. During the weekday the classrooms are fully occupied from 7:30h to 11:00h and from 13:30 to 17:30h. Both offices have no regular occupancy, but it is assumed that the greater number of people, for example during reunions could happen at any time (7:30h – 17:30).

Around 110 people are usually present in the building, seated and doing light work, thereby 97 W per children can be calculated accordingly, this translates to 10.7 kW. The lighting load is 15 W/m^2 by an area of 170m^2, which reveals a total lighting load of 2.6 kW. The electrical devices e.g. computer, monitor etc. produce a thermal load of 3.6 kW. According to this assumption the total internal load is 17kW.

The thermal behavior of the building will be assessed in an hourly daily simulation figure. The simulation is realized with two different indoor set point temperatures in the relevant space. These are 20°C and 26°C. In Brazil, the air-conditioning systems are often oversized, thus the indoor temperature variates between 18°C - 20°C during the whole year. For this reason 20°C was chosen to show how high the cooling load is, hence the energy consumption in comparison to an intended indoor temperature of 26°C. This temperature range is in accordance with the Brazilian standards (PNB-10).

The indoor air temperature Ti is the most evident indicator of proper thermal comfort, the temperature should be higher on lower activity level and the use of lighter clothing. For building cooling it is important that our body is capable to adapt to seasonal conditions. Air humidity affects the latent heat transfer from the bodies to the surrounding air. Therefore in case of higher temperatures the humidity has to be lower. [8]

External Temperature	Internal Conditions		
dry-bulb temperature [°C]	dry-bulb temperature [°C]	wet-bulb temperature [°C]	relative umidity [%]
29	24,5	19,5	62,0
	25,0	19,0	56,0
	25,5	18,5	50,0
	26,0	18,0	44,0
32	25,0	20,5	66,0
	25,5	20,0	60,0
	26,0	19,5	54,0
	26,5	19,0	48,0
35	25,5	21,5	70,0
	26,0	21,0	64,0
	26,5	20,5	58,0
	27,0	20,0	52,0

Table 7 - Internal thermal comfort conditions regarding the ambient summer temperatures (PNB-10, Brazil) [17]

3.2.1.2 Results of the simulation

Diagram 4 presents the daily thermal behavior of the building in the worst scenario. With an indoor air temperature of Ti = 26°C the maximum cooling load is 125560.2 BTU/h (~36.8 kW). Diagram 5 shows the graph of the cooling load at Ti=20°C. The maximum amount is 157687.9 BTU/h (~46.2 kW).

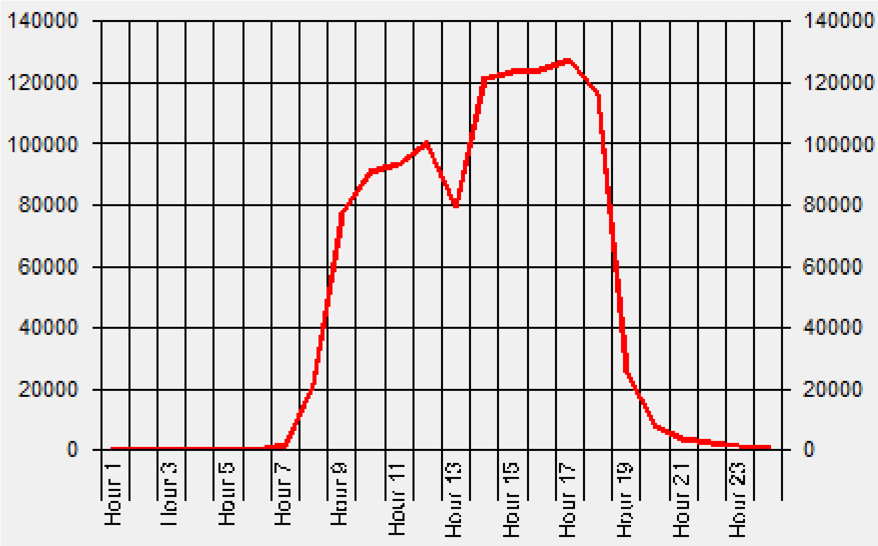


Diagram 4 - Screenshot "HvacLoadExplorer" – Total Cooling Load (Btu/h) by Ti=26°C during a hot summer day

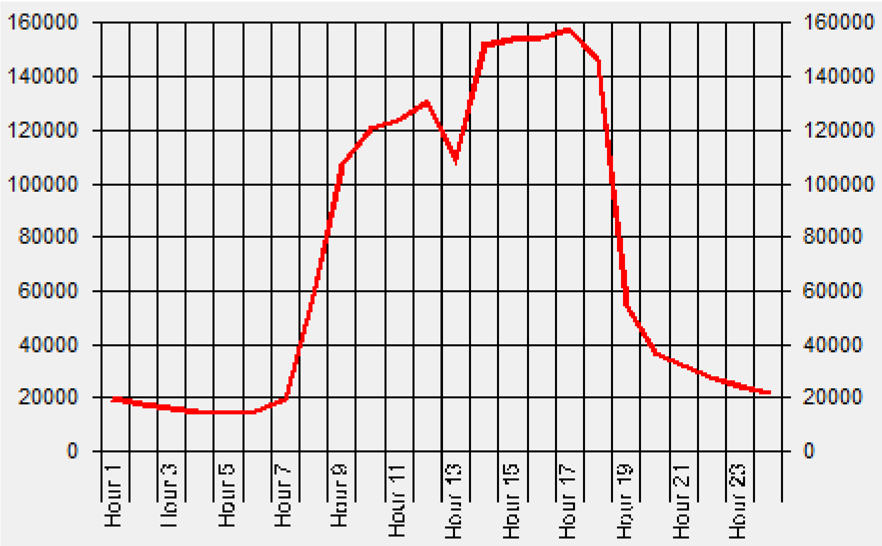


Diagram 5 - Screenshot "HvacLoadExplorer" – Total Cooling Load (Btu/h) by Ti=20°C during one hot summer day

The abatement of the graph at 1pm is caused by the lower internal cooling load. During lunchtime the students are leaving the classroom.

3.2.1.3 Conclusion

The existing cooling system covers the thermal loads in almost every room. The simulation for the different indoor air temperatures shows that the total cooling load rises up to 9.6 kW by an ΔTi = 4°C. Diagram 6 presents the different thermal behavior of both indoor air temperatures during a hot summer day (worst case scenario).

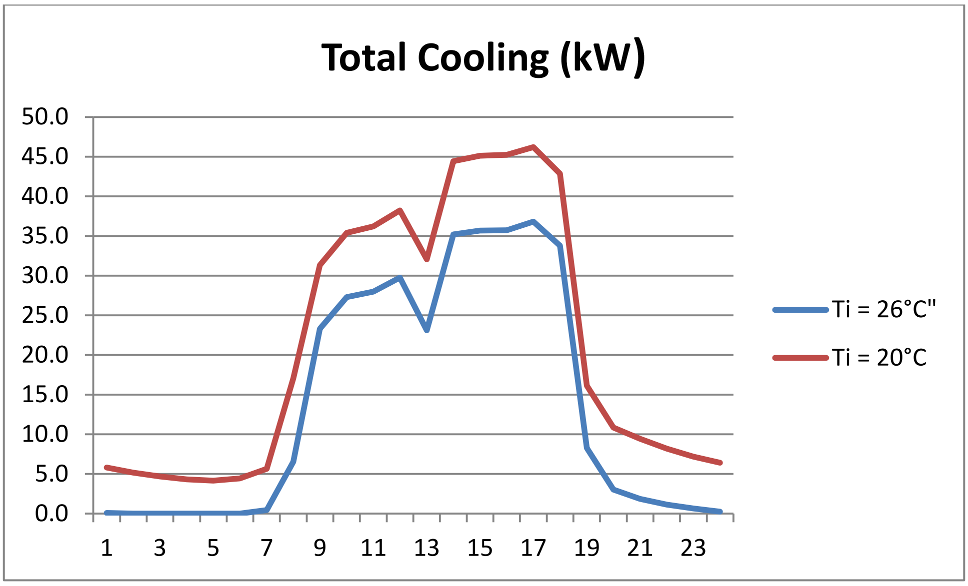


Diagram 6 - Comparison of the total cooling load with different indoor air temperatures

Indoor Set Point Temperature Ti [°C]	Maximum Cooling Load [kW]	Specific Cooling Load [kW/m²]
20	46.2	272
26	36.8	216

Table 8 - Cooling load results

In the next chapter the suitable air-conditioning system will be chosen, which refers to the simulated cooling load at an indoor air temperature of Ti=26°C.

3.2.2 Selection and Design of the Equipment

The selection and design will be analog to an existing cooling system of an auditorium in the UNESP University in Guaratinguetá. [4]

It concerns a closed cycle process and consists of different subsystems (Table 9).

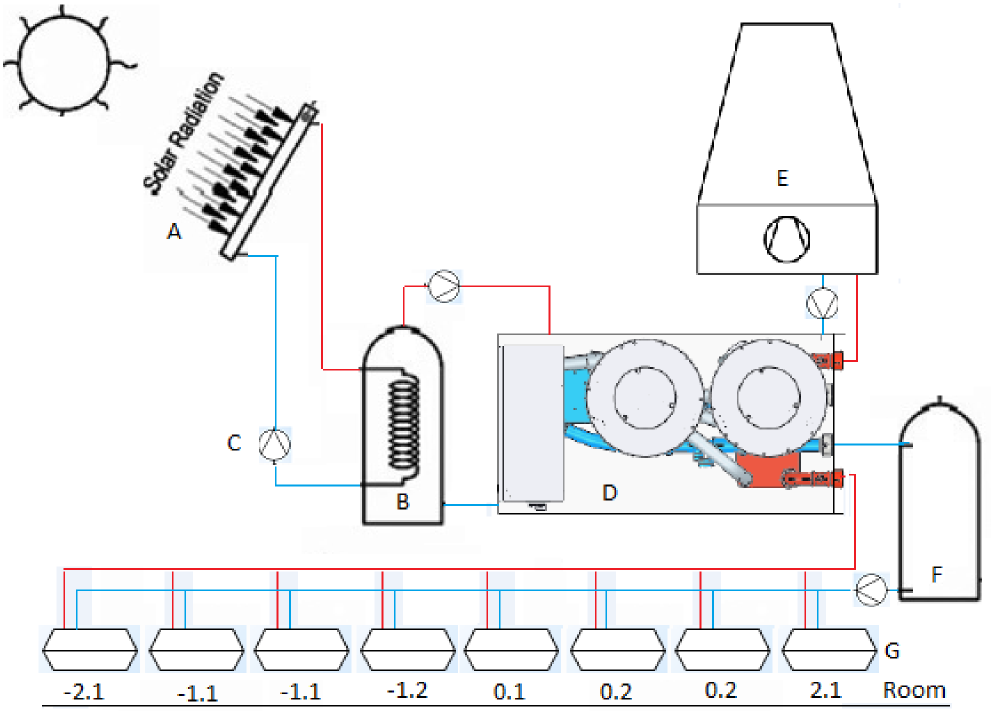


Figure 18 - Schematic diagram of the simulated solar-assisted air conditioning system for the primary school

Heat Production Subsystem		
A	Flate Plate collectors	80 m²
B	Hot Water Storage	1000l
C	Pump	
Cold Production Subsystem		
D	Absorption chiller	35 kW
E	Wet Cooling Tower	
C	2 x Pump	
Load Subsystem		
F	Cold Water Storage	1000l
G	8 x Fan Coil	4 - 5 kW
C	Pump	

Table 9 - Technical components of the different subsystems

The heat production subsystems consist mainly of 80m^2 thermal solar collector fields, which serves the hot water tank with an in- and output temperature of 88°C and 83°C. The cold production system contains a 35 kW absorption chiller and a cooling tower. The thermal compressor of the absorption chiller is served by the provided heat from the hot water tank. The load subsystem is built up by a cold water tank, the distribution system and 8 fan coils.

3.2.2.1 Results

Diagram 7 shows that the solar congruence is mostly covering the cooling demand. At night the building cooling load is often higher than the cooling capacity and at noon the cooling capacity is around twice as much the demand. Therefore the water storages are coming into operation.

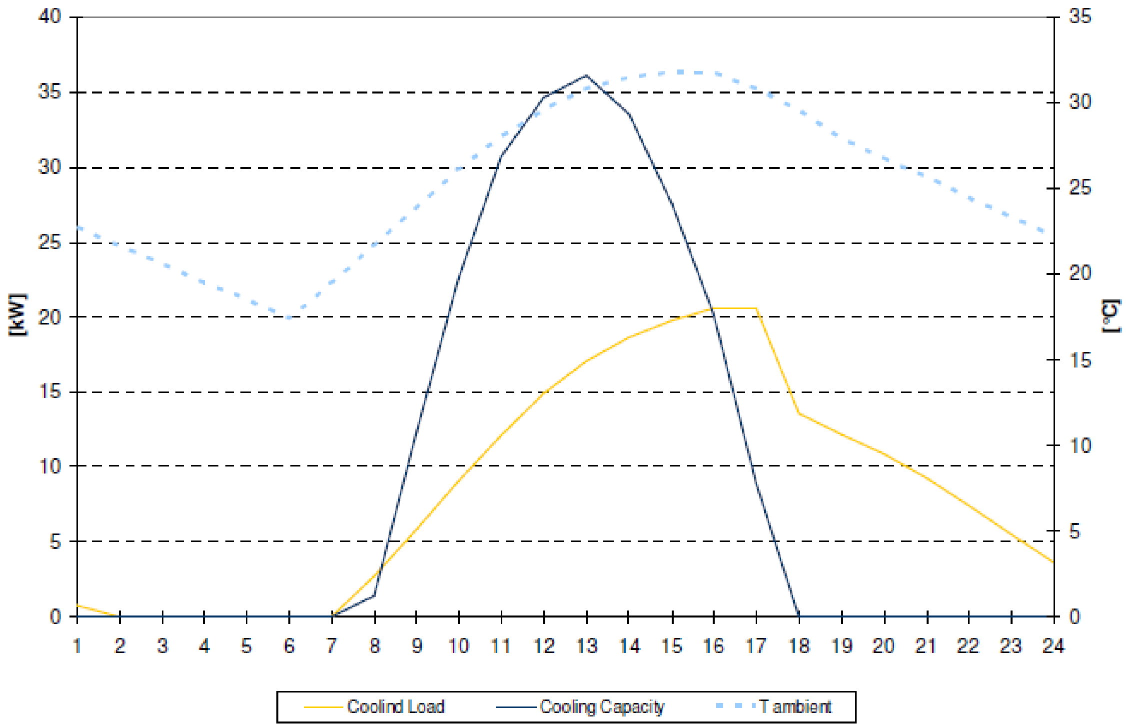


Diagram 7 - Predicted correlation between cooling demand and cooling yield during a summer day with high solar irradiation (ca. 1100 W/m^2) [4]

During the night the primary school is out of service, hence the cooling demand occurs during the day. Furthermore the outside temperatures during summer night in Rio de Janeiro are relatively low because of the cold ocean current (Diagram 4 - Screenshot "HvacLoadExplorer" – Total Cooling Load (Btu/h)). Thus the cooling load reduces substantially and the water storage capacity can be dimensioned at a lower capacity or rather eliminated.

The main advantage is that the cooling load and solar gain occurs at the same time. Diagram 8 shows the predicted total monthly cooling demand and the available yield of thermal energy regarding the cooling system of the University in Guaratinguetá. The cooling demand during July is almost null and the potential cooling yield is comparatively high. During the winter the primary school in Rio de Janeiro has a high internal thermal load; hence it can use the potential cooling yield during all-season.

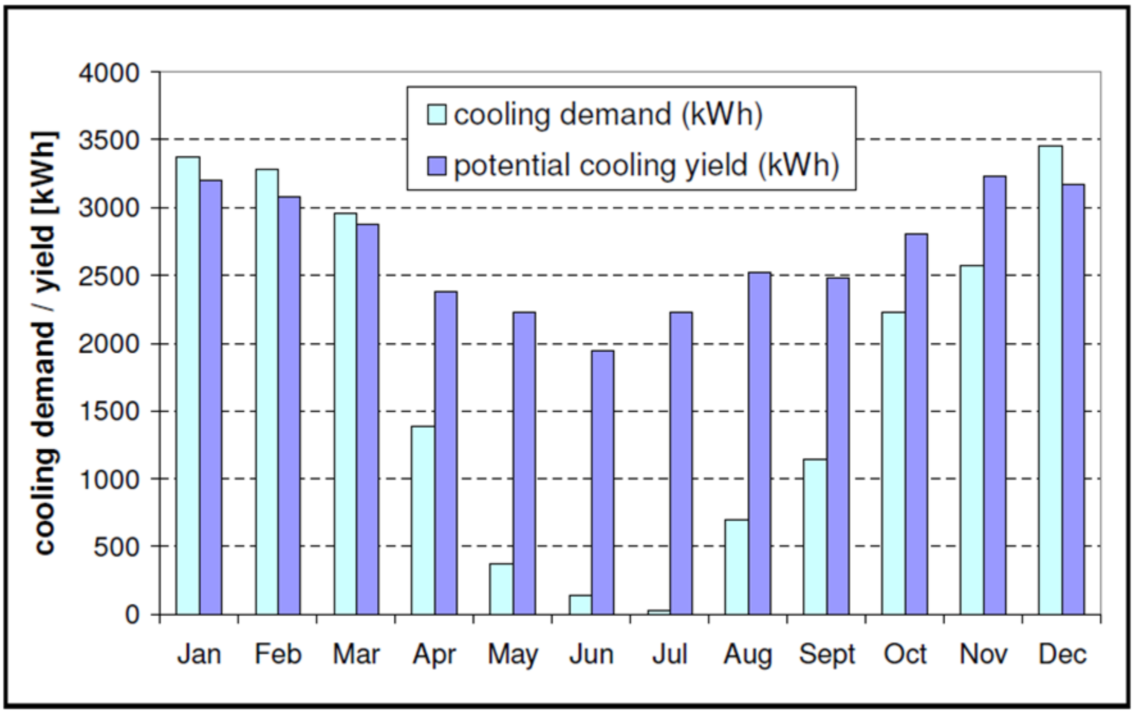


Diagram 8 - Predicted total monthly cooling demand and available yield of thermal energy (8760 h). Solar yield is calculated with an constant daily average collector efficiency of 0,38 m^2 collector array and a constant Chiller COP of 0,7 [4]

3.2.3 Economic Assessment

According to Table 14 the specific investment cost for such a cooling system without a back-up application and smaller water storages is 3000 R$/kW. The cooling system is dimensioned to cover a thermal load of 35 kW. Therefore the total investment costs rise up to 105.500 R$.

Electricity Consumption & Operation Cost		
Component	Solar assisted system	Existing cooling system
4 x Water Pumps	360 W	
Wet Cooling Tower Fan	280 W	
35 kW Absorption Chiller	210W	
8 x Fan Coil Units	600 W	
5 x Window Air-Conditioner		35,8 kW
Total	1450 W	35,8 kW
Total (1 Year)	2152 kwh*	9577 kWh**
Operation costs (1 Year) by 0.898 R$/kWh (Rio de Janeiro)	1930 R$	8600 R$

*Energy consumption per year (10h; 22 days/month)
** Results from 3.1 Inventory Analysis

Table 10 - Comparison of electricity consumption and operation cost of a solar assisted air conditioning system and the existing cooling system

According to the operation costs the payback time for the investment is 15.8 years, thus the system would bring an income during its lifespan of 20 years.

3.2.4 Environmental Benefits

To estimate the corresponding specific CO_2 emissions per kWh produced ‘cold’ (per 0.285 TR), a conversion factor of 0.28 kg CO_2 per kWh electricity is applied (average for the interconnected Brazilian electricity grid) [1].

Table 11 shows the CO_2 savings per year.

Electricity Consumption per Year [kWh]		CO2 -Emissions [kg]
Solar Assisted System	2152	603
Existing System	9577	2682
CO2 Saving per Year		2079

Table 11 - CO2 savings per year calculated with the conversion factor of 0.28 kg CO2 per kWh electricity

The main motivation of solar cooling technology implementation and replacing the conventional system is that they have a lower environmental impact. Any primary energy savings result in CO2 reduction.

In addition to the CO2 savings, the usage of environmentally refrigerants must be pointed out. They have no ozone-depleting or global warming potential. In the conventional systems are often used the R-134a as refrigerant.

A negative point is the water consumption of the wet cooling-tower. However, the water amount is very small in this case only 50 liters per day. This water could be collected by rain and therefore it causes no negative environmental impact. In order to complete the environmental impact evaluation of solar-assisted air-conditioning system a complete life cycle analyses should be carried out, but this would go beyond the scope [4].

4 Conclusion

Generally, in all calculated cases the solar cooling low operation cost compensate the higher investment cost in a long term, especially in Rio de Janeiro at a higher electricity price. The case study shows that solar cooling systems can be an alternative option against electric split chillers, especially in areas with significant cooling demand (high internal cooling load), solar irradiance, and electric prices [4].

The electricity prices in Rio have almost doubled the past two years (from R$ 0,48 kWh in 01/2014 to R$ 0,90 kWh in 01/2016). As electric rates increase, solar cooling will become an even more economically attractive option for building owners.

Through the case study was the economic feasibility of the specified solar-assisted air-conditioning checked and compared with a conventional electrically driven compression split air-conditioning system. It turned out, that the low operation cost can compensate the higher investment cost within the solar cooling system life time of minimum 20 years.

Last but not least, a recommendation regarding “solar cooling” integration in high buildings. In Tropical Cities sufficient roof area for providing a whole skyscraper with solar air-conditioning is often not given. Through a rough estimation can be said that only for two stores enough roof space exists. Hence it is recommendable to use an electrically driven compression central chiller to cover the latent cooling loads and use a solar cooling system in side-stream to cover the highest cooling loads during the day. Thus extra capacity generated by the sun occurs only when the load is the greatest, and the energy source to drive it has no recurring cost.

In future the Brazilian government intends to secure the country's electricity supply by more nuclear power and fossil-fueled thermal power stations. Energy efficiency measures like solar cooling implementation can contribute to less electric energy consumption. Certainly, it does not solve the country’s energy problem, but if the whole country cooling demand would be supplied by solar cooling systems more or less one large-scale power plant could be avoided. Solar cooling technology is a way to provide building air-conditioning by using local regenerative sun energy [4].

5 References

[1]. **Fraunhofer Institut for Solar Energy Systems ISE.** *Solar cooling in Brazil - Technology study.* 2009.

[2]. **SHC, Solar Heating & Cooling Programme IEA.** *Solar Air-Contidioning and Refrigeration.* 2011.

[3]. **IRENA, International Renewable Energy Agency.** *Renewable Energy Policy Bief.* Brazil : s.n., June 2015.

[4]. **Reichhardt, Till Felix.** *Technical and Economic Assessment of Medium Sized Solar-Assisted Air-Conditioning.* Rio de Janeiro : s.n., 2010.

[5]. **Solair.** *Requirements on the design and configuration of small and medium sized solar air-conditioning applications - Guidelines.* 2009.

[6]. **Henning, H.M.** *Solar Cooling Position Paper.* Freiburg, Germany : IEA SHC, 2011.

[7]. **Wikipedia.** *Photovoltaics.*

[8]. **Riifel, D.** *Estudo Teórico e Experimental da Dinâmica e da Otimização de Refrigeradores Térmicos por Adsorção.* Universidade Federal da Paraíba : s.n., 2008.

[9]. **ASHRA.** *ASHRAE Terminology of HVAC&R.* Atlanta : s.n., 1991.

[10]. **Jakob and Mugnier.** *International Sustainable Energy Review.* 2012.

[11]. **Carrier United Technologies.** *Technical Data Sheet.* 2012. Lithium Bromide Absorption Chiller 16JLR.

[12]. **INMET Brazilian National Institue of Meteorologogy.** *Averaged metological data.* Brazil : s.n., 2000.

[13]. *Aeroporto e favela captam agua da chuva.* **UOL.** Rio : s.n.

[14]. **Procel; Eletrobras.** *Participação dos eletrodomésticos no consumo de eletricidade das residências, Brasil.* Brazil : s.n., 2007.

[15]. **Procel.** *Dicas de Economia de Energia.* Brazil : s.n., 2006.

[16]. **ABNT.** *Cental and unitary air conditioning systems .* Brazil : s.n., 2008.

[17]. **Hagel, A.** *Análise computacional da demanda energética de climatização de edifício, projeto de graduação.* Universidade de Brasília : s.n., 2005.

[18]. **MatWeb.** *Unit of Measure.* 2016.

[19]. **Jakob, U.** *Solar Cooling in Europe .* New Castle, Australia : s.n., 2009.

[20]. **Wikipedia.** *Rio de Janeiro.*

6 Appendix

PROCEL PROGRAMA NACIONAL DE CONSERVAÇÃO DE ENERGIA ELÉTRICA — Eletrobras

Tabela de estimativa de consumo médio mensal de eletrodomésticos de acordo com um uso hipotético

Para calcular o consumo médio (kWh) de um equipamento, de acordo com o seu real hábito de uso, procure a potência do aparelho no manual do fabricante.

Em seguida, faça o cálculo da seguinte forma:

Consumo médio do equipamento (kWh) = Potência do equipamento (W)/1000 x Número de horas utilizadas x Número de dias de uso ao mês

Para achar o custo mensal em reais, multiplique o consumo médio em kWh pelo valor da tarifa cobrada pela concessionária local.

APARELHOS ELÉTRICOS	DIAS ESTIMADOS	MÉDIA	CONSUMO MÉDIO MENSAL
	Uso/Mês	Utilização/Dia	(KWh)
APARELHO DE BLU RAY	8	2 h	0,192
APARELHO DE DVD	8	2 h	0,240
APARELHO DE SOM 3 EM 1	20	3 h	6,600
AQUECEDOR DE AMBIENTE	15	8 h	193,440
AQUECEDOR DE MAMADEIRA	30	15 min	0,750
AQUECEDOR DE MARMITA	20	30 min	0,600
AR CONDICIONADO TIPO JANELA MENOR OU IGUAL A 9.000 BTU	30	8 h	128,800
AR CONDICIONADO TIPO JANELA DE 9.001 A 14.000 BTU	30	8 h	181,600
AR CONDICIONADO TIPO JANELA MAIOR QUE 14.000 BTU	30	8 h	374,000
AR CONDICIONADO TIPO SPLIT MENOR OU IGUAL A 10.000 BTU	30	8 h	142,288
AR CONDICIONADO TIPO SPLIT DE 10.001 A 15.000 BTU	30	8 h	193,760
AR CONDICIONADO TIPO SPLIT DE 15.001 A 20.000 BTU	30	8 h	293,680
AR CONDICIONADO TIPO SPLIT DE 20.001 A 30.000 BTU	30	8 h	439,200
AR CONDICIONADO TIPO SPLIT MAIOR QUE 30.000 BTU	30	8 h	679,200
ASPIRADOR DE PÓ	30	20 min	7,170
BATEDEIRA	8	20 min	0,400
BOILER ELÉTRICO DE 200 L	30	24 h	346,750
BOMBA D'ÁGUA 1/2 CV	30	30 min	7,200
BOMBA D'ÁGUA 1/3 CV	30	30 min	6,150
CAFETEIRA ELÉTRICA	30	1 h	6,565
CAFETEIRA EXPRESSO	30	1 h	23,820
CHALEIRA ELÉTRICA	30	1 h	28,230
CHURRASQUEIRA ELÉTRICA	5	4 h	76,000
CHUVEIRO ELÉTRICO - 4500 W	30	32 min	72,000
CHUVEIRO ELÉTRICO - 5500 W	30	32 min	88,000
COMPUTADOR	30	8 h	15,120
ENCERADEIRA	2	2 h	1,800
ESPREMEDOR DE FRUTAS	20	10 min	0,187
EXAUSTOR FOGÃO	30	2 h	9,960
FAX MODEM EM STAND BY	30	24 h	2,160
FERRO ELÉTRICO AUTOMÁTICO A SECO - 1050 W	12	1 h	2,400
FERRO ELÉTRICO AUTOMÁTICO A VAPOR - 1200 W	12	1 h	7,200
FOGÃO ELÉTRICO - COOK TOP (POR QUEIMADOR)	30	1 h	68,550
FORNO ELÉTRICO	30	1 h	15,000
FORNO MICRO-ONDAS - 25 L	30	20 min	13,980
FREEZER VERTICAL/HORIZONTAL	30	24 h	47,550
FREEZER VERTICAL FROST FREE	30	24 h	54,000
FRIGOBAR	30	24 h	18,900
FRITADEIRA ELÉTRICA	15	30 min	6,810
FURADEIRA	4	1 h	0,944
GELADEIRA 1 PORTA	30	24 h	25,200
GELADEIRA 1 PORTA FROST FREE	30	24 h	39,600
GELADEIRA 2 PORTAS	30	24 h	48,240
GELADEIRA 2 PORTAS FROST FREE	30	24 h	56,880
GRILL	10	30 min	3,205
HOME THEATER - 350 W	8	2 h	5,600

Página 1 de 2

Table 12 - Tabela de estimativa de consumo médio mensal de eletrodomésticos de acordo com um uso hipotético

Tabela 1 (continuação)

Local	D pessoas/ 100 m²	Nível 1		Nível 2		Nível 3		Exaustão mecânica L/s* m² [a]
		F_p L/s*pess.	F_a L/s*m²	F_p L/s*pess.	F_a L/s*m²	F_p L/s*pess	F_a L/s*m²	
Edifícios públicos								
Aeroporto – saguão [c]	15	3,8	0,3	5,3	0,4	5,7	0,5	--
Aeroporto – sala de embarque [c]	100	3,8	0,3	5,3	0,4	5,7	0,5	--
Biblioteca	10	2,5	0,6	3,5	0,8	3,8	0,9	--
Museu, galeria de arte [d]	40	3,8	0,3	5,3	0,4	5,7	0,5	--
Local de culto	120	2,5	0,3	3,5	0,4	3,8	0,5	--
Legislativo – plenário	50	2,5	0,3	3,5	0,4	3,8	0,5	--
Teatro, cinema, auditório – *lobby*	150	2,5	0,3	3,5	0,4	3,8	0,5	--
Teatro, cinema, auditório e platéia	150	2,5	0,3	3,5	0,4	3,8	0,5	--
Teatro, cinema, auditório – palco	70	5	0,3	6,3	0,4	7,5	0,5	--
Tribunal – sala de audiências	70	2,5	0,3	3,5	0,4	3,8	0,5	--
Esportes								
Boliche – área do público	40	5	0,6	6,3	0,8	7,5	0,9	--
Ginásio coberto (área do público)	150	3,8	0,3	4,8	0,4	5,7	0,5	--
Ginásio coberto (quadra)	--	--	0,3	--	0,4	--	0,5	--
Piscina coberta [e]	--	--	2,4	--	3,0	--	3,6	2,5
"Fitness center" – aeróbica	40	10	0,3	12,5	0,4	15,0	0,5	--
"Fitness center" – aparelhos	10	5	0,6	6,3	0,8	7,5	0,9	--
Estabelecimentos de ensino								
Sala de aula	35	5	0,6	6,3	0,8	7,5	0,9	--
Laboratório de informática	25	5	0,6	6,3	0,8	7,5	0,9	--
Laboratório de ciências	25	5	0,9	6,3	1,1	7,5	1,4	5,0
Hotéis								
Apartamento de hóspedes	.	5,5	--	6,9	--	10,3	--	--
Banheiro privativo	--	--	--	--	--	--	--	2,5/unid.
Lobby, sala de estar	30	3,8	0,3	4,8	0,4	5,7	0,5	--
Sala de convenções	120	2,5	0,3	3,1	0,4	3,8	0,5	--
Dormitório coletivo	20	2,5	0,3	3,1	0,4	3,8	0,5	--
Restaurantes, bares, diversão								
Restaurante – salão de refeições	70	3,8	0,9	4,8	1,1	5,7	1,4	--
Bar, salão de coquetel	100	3,8	0,9	4,8	1,1	5,7	1,4	--
Cafeteria, lanchonete, refeitório	100	3,8	0,9	4,8	1,1	5,7	1,4	--
Salão de jogos	120	3,8	0,9	4,8	1,1	5,7	1,4	--
Discoteca, danceteria	100	10,0	0,3	12,5	0,4	15,0	0,5	--
Jogos eletrônicos	20	3,8	0,9	4,8	1,1	5,7	1,4	--

Table 13 - Minimum air exchange [18]

MatWeb has also provided a reference table for converting between English and Metric units.

To Convert From:	To:	Multiply By:
lb_f/in^2 (psi)	pascal (Pa)	6894.757
pascal (Pa)	lb_f/in^2 (psi)	1.4504E-4
g/cm^3	lb/ft^3	62.427974
lb/ft^3	kg/m^3	16.01846
lb/in^3	kg/m^3	27,679.90
lb/ft^3	g/cm^3	0.01601846
volts/mil	kV/mm	0.039370
mil (0.001 inch)	cm	2.54E-3
cm	mil	393.70
$MPa(m^{1/2})$	$psi(in^{1/2})$	910.06
J/(g-°C)	BTU/(lb-°F)	0.239006
BTU/(lb-°F)	J/(g-°C)	4.184000
joule (J)	cal (thermochemical)	0.2390057
cal (thermochemical)	joule (J)	4.184000
joule (J)	BTU (thermochemical)	9.4845E-4
BTU (thermochemical)	joule	1054.350
µm/(m-°C)	µin/(in-°F)	0.55556
µin/(in-°F)	µm/(m-°C)	1.80
cm^3/Kg	in^3/lb	0.027680
in^3/lb	cm^3/kg	36.127
W/(m K)	BTU in /(hr ft^2 F)	6.9334713
BTU in /(hr ft^2 F)	W/(m K)	0.1441314
(J m)/(min m^2 C)	W/(m-K)	0.016667
W/(m-K)	(J m)/(min m^2 C)	60

ACQUISITION COST [R$]			SPECIFIC COST [R$ per kW cooling capacity]	
Component	A: complete solar cooling "kit"	B: individual comp.	A:	B:
Flate Plate collectors, 80 m² Bosch Bruderus Logasol SKN 3.0	37.234 (13.790 €)	37.234 (13.790 €)	1.064	1.064
SolarNext chillii ® Cooling Kit WFC35, incl.: 1 x Yazaki WFC-SC10 Absorption chiller 1 x wet cooling tower with auto accessories filling and emptying, and fan speed control 1 x hot water pump 1 x cooling water pump 1 x chillii ® System Controller HC incl. Temperature Sensors 1 x cold storage 2000 l without Insulation 1 set of sensors f. Chilled water storage 1 x pump f. cold distribution with accessories 1 x hot water storage 2000 l with insulation 1 set of sensors f. hot water storage 2 x changeover valve with actuator	126.700 (46.926 €)	18.225 (6.750 €) estimated price for all these comp. except: chiller, cooling tower and controller	3.620	
1 x pump f. solar collector cuircit	945 (350 €)	945 (350 €)		
4 x fan coil unit	10.268 (3840 €)	10.268 (3840 €)	293	293
Yazaki WFC-SC10 35 kW Absorption Chiller		43.501 (16.700 €)		1.242
wet cooling-tower F-32 Refrigeracao International		7.370 (2.729 €)		211
SolarNext chillii ® System Controller H		5.624 (2.083 €)		
4 x Split Air-conditioner back-up* Electrolux SPLIT SE 30 F (30.000 BTU / 8,8 kW)	16.000 (5.926 €)	16.000 (5.926 €)	457 (169 €/KW)	457 (169 €/KW)
TOTAL	191.147 (70.772 €)	139.167 (52.178 €)	5.461 (2.022 €/KW)	3.976 (1473 €/KW)

Notes: a) Conversion factor 2,7 R$/€; b) * In accordance with PROCEL, as Back-up was chosen a split-conditioning system, because of the possibility to compare both systems by checking actual measuring data; c) A includes a complete cooling “kit” available by SolarNext AG company in Germany; d) B includes the acquisition prices for individual ordered components as the wet cooling tower, directly from a Brazilian company and the chiller directly from Yazaki, Japan. At last the controller device from SolarNext, too.

Table 14 - Acquisition and specific costs per kW cooling capacity for two different system combinations [4]