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Faculty of Civil Engineering,
Institute of Heat, Gas and Water Technology

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PHOTOVOLTAIC
SOLAR AIR CONDITIONING

Summary of the Doctoral Thesis

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I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences is my own and does not contain any unacknowledged material from any source. I confirm that this Thesis has not been submitted to any other university for the promotion to other scientific degree.

Andrejs Snegirjovs.............

Date:...................................

The doctoral thesis has been written in English: It contains abstract, introduction, five chapters, conclusions and bibliography with 51 reference sources. It has been illustrated by 63 figures and 6 tables. The volume of the Doctoral Thesis is 105 pages.

SYMBOLS AND ABBREVIATIONS

AB	ABsorption,
AC	Alternating Current,
AD	ADsorption,
BS	Base System,
CAC	Conventional Air Conditioning,
CAC&H	Conventional Air Conditioning and Heating,
COP	Coefficient of Performance,
CS	Cold Storage,
DC	Direct Current,
DHW	Domestic Hot Water,
EF	Emission Factor, kg of CO$_2$ / W·h,
G	Irradiation of the inclined surface, W·h/m^2 per year,
G_h	Global solar irradiation of a horizontal surface, W·h/m^2 per year,
GHG	Greenhouse gas,
HP	Heat Pump,
HS	Hot Storage,
HVAC	Heating, Ventilation and Air Conditioning,
NG	Natural Gas,
OU	Outdoor Unit (a heat rejection tower),
P	Electrical power, W,
PEF	Primary Energy Factor, W·h,
PV	PhotoVoltaic,
PV-SAC	PhotoVoltaic Solar Air Conditioning,
Q	Energy, W·h,
$\dot{Q}$	Heat flow rate, W,
RES	Renewable Energy Sources,
RT	Room Temperature, °C,
SAC	Solar Air Conditioning,
SEER	Seasonal Energy Efficiency Ratio,
T, t_i	Temperature, K and °C.

ABSTRACT

The theme of the Doctoral Thesis is “Photovoltaic Solar Air Conditioning” (PV-SAC).

The objective of this study is to develop, to test and to evaluate the technology of the enhanced grid-connected photovoltaic solar air conditioning.

Ever-decreasing costs of system components combined with energy-efficient concepts in the area of solar energy technologies open new opportunities for application of hot- and cold-storage systems in different building sectors. In the current market situation, photovoltaic electric-driven compression chillers are more profitable as compared with solar thermal-driven sorption cooling devices due to a smaller size of their components such as compressor and heat rejection unit.

In the research, a concept has been developed for the solar air conditioning system operating on PV electric energy, in which cooling by a compression chiller is combined with free cooling. The PV-SAC system is intended for a single-family house. The definition and analysis of the working parameters and of the system yield are presented.

The PV-SAC research has been carried out in two parts: 1. Dynamic simulation of a system model (for three different climatic zones) in the Polysun® program software. 2. A real system operation in a temperate climatic zone. The system is compared with that based on the sorption solar air conditioning technologies.

The research results have been reported at 11 international scientific conferences and are described in 28 publications. The Doctoral Thesis consists of five chapters; it has been illustrated by 63 figures and 6 tables, and its volume is 105 pages. In the Thesis, 51 literature sources have been used.

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INTRODUCTION

Novelty of the Research

Information on the electrical-driven solar air conditioning (SAC) is rather scanty. A considerable body of technical data mostly concerns large-scale photo-voltaic solar air conditioning systems. Reliable information about the energy output has arisen only in the last years; however, it is still not easily accessible, and sometimes its sources are closed. Despite all that, a great interest in this type of SAC systems comes from solar energy researchers, observers and designers. In this study, performance evaluation is performed for the PV-SAC technology, in which low-power (up to 15 kW_P of cooling power on average) systems are used. Such a system contains a PV electric-driven compression chiller with cold and heat sensible thermal storage capacities, and a rejected energy unit used for preheating domestic hot water (DHW). In a non-cooling season it is possible to partly employ the system in the reverse mode for DHW production. In this mode the ambient air serves as a heat source. Besides, free cooling is integrated in the PV-SAC concept.

Objective and tasks

The objective of this study is to develop, to test and to evaluate technology of the enhanced grid-connected Photovoltaic Solar Air Conditioning.

The main tasks of the study:

1) To develop and test a PV-SAC pilot system by driving it in real weather conditions.
2) To evaluate the energy consumption and output of PV-SAC system using dynamic simulation of a system model in Polysun® software.
3) To evaluate the potential of a PV-SAC system implemented in common HVAC engineering field.

4) To determine the influence of PV-SAC system components on its yield and working parameters.
5) To compare the PV-SAC technology with the most common solar air conditioning technologies (ADsorption, ABsorption, Simple PV-SAC).
6) To evaluate the PV-SAC system productivity in different climatic conditions.
7) To assess its economic and ecological impact.
8) To determine the potential of enhanced grid-connected PV-SAC system.

Relevance of the Thesis

Expected increase in the cooling loads for comfort needs in private and office buildings calls for alternatives to the conventional energy sources in order to reduce global greenhouse gas emissions, e.g., CO_2. Reduction in the component costs and innovative solutions in the area of solar energy technologies opens wider opportunities for their application in different building sectors. The solar cooling communities from SHC IEA are reporting about the increase in the number of solar cooling and air conditioning systems in the last decade. These authors offer several ways for conversion of the solar radiation into cold using solar cooling components. Today, the most popular technologies are thermal-driven ab- and adsorption chillers in combination with solar thermal collectors. However, due to high costs of the sorption machines and collectors, the market for these technologies is growing very slowly. At the same time, the photo-voltaic (PV) market develops fast, with a continuously reduced PV module prices. This economical reason increases the attractiveness of solar-electrical air conditioning systems. Therefore, the coupling of PV modules with an electrical-driven system of the type presents the concept of PV-based air conditioning. It should be noted that all components of PV electricity driven air conditioning systems are commercially available.

Electric-driven heating and cooling equipment, such as vapour compression heat pumps (HPs), chillers or reversible HPs, in connection with hot and/or cold storages is an attractive option for the energy supply in buildings. However, except for some European regions, today only a few complete system solutions using photovoltaics for the energy supply in buildings are available on the market. Therefore, a lack of information on the overall cost and performance of such systems is identified.

1 EVALUATION OF PV-SAC POTENTIAL

Cold generation and other cooling operations imply the heat rejection from the operation field. Therefore, the notion “air conditioning” mainly relates to heat rejection, while it might include heating in some cases.

Ever-rising comfort requirements in buildings and transportation makes the cooling demand and thus the cooling market growing. These comfort requirements are leading to the air conditioning as a necessity in commercial buildings, and is not anymore seen as a luxury. With these premises and the aim of GHG reduction, a fast growing market of solar air conditioning systems can be expected. This has remained relatively unnoticed by policy makers, partly because cooling needs are traditionally being met by electrical air conditioners, hiding the cooling element within the building overall electricity consumption.

In Europe, a rise in the share of commercial buildings equipped with cooling systems is expected to reach at least 60 % by the year 2020. The maximum potential cooling demand in Europe – if 100 % of all useful space would be air-conditioned – is estimated to be annually 1400 TW·h cooling.

Solar cooling communities expect an impetuous solar cooling development in nowadays growing use of renewable energy sources (RES). This rise in RES implementation in energy sector gets support from EU directive and regularities of energy use. The recent building directive 2009/28/EC has a subtask of decreased cooling load development. Not less impact has had a directive "2020 concerning nearly zero energy buildings", which means that direct fossil fuel and electricity consumptions should predictably decrease. Indeed, it is possible to reduce the energy consumption instead of reducing the comfort level by using energy saving technology as well in solar air conditions. But this also means that significant changes are coming and big work has to be done in the nearest future. Nowadays, many research institutes are engaged in development of direct and indirect solar air conditioning technologies.

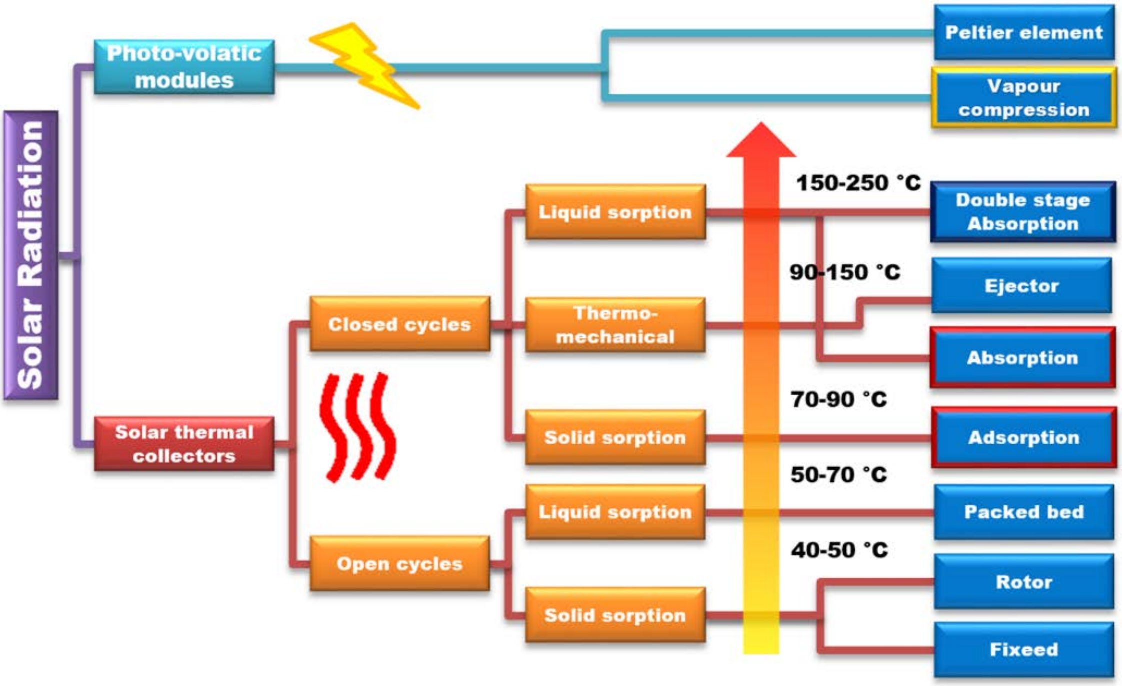


Fig. 1.1. Solar cooling technology tree.

The solar cooling technology tree shown in Fig. 1.1 was obtained by summarising the latest information from different sources.

Solar cooling can be passive and active. Passive solar cooling implies the absence of external energy inflow; systems of the type are not observed in this Thesis. In turn, active solar cooling as a driving source uses electricity or heat energy. The heat energy for thermal-driven chillers is produced mostly by solar collectors. Electricity for electric-driven chillers is obtained from photo-voltaic panel arrays, or from large solar stations via steam turbines. A solar cooling technology is usually chosen according to the energy source, the area of applications and the weather conditions.

2 EXPERIMENTAL PV-SAC SYSTEM

At the Institute for Solar Technology SPF (Rapperswil, Switzerland) a pilot small-scale PV-SAC system has been developed and built up.

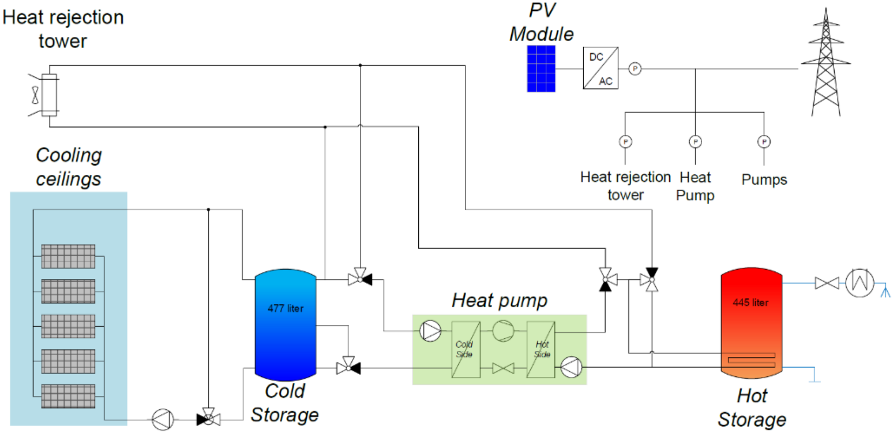


Fig. 2.1. Schematic of the photovoltaic solar air conditioning system

The main components of the PV-SAC (Figs. 2.1, 2.2) forming a reference system are photovoltaic modules combined with a DC/AC inverter, electric-driven chiller, indoor cold distribution elements (cold ceilings) and outdoor heat rejection unit. The pilot system under consideration also contains a hot storage, cold storage, and heat rejection tower (outdoor unit) for the preheating of domestic hot water (DHW).

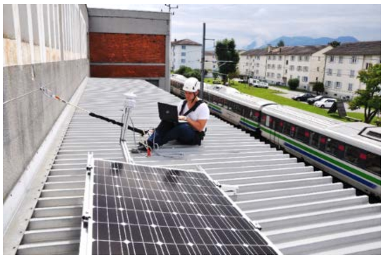
PV modules	Cooling Machine Hot Storage	Outdoor Unit (Heat Rejection Tower)
		
Cooling Ceilings	Cold Storage	Measurement equipment
		

Fig. 2.2 Main parts of PV-SAC

For accrued determination of the system cooling and heating yields as well as of the system operating parameters, deep investigation should be performed.

3 EXPERIMENTAL VERIFICATION OF PV-SAC SYSTEM PERFORMANCE

The pilot PV-SAC system performance has been verified in real weather conditions. The system mostly operates under autonomous regime. Besides, specific experiments have been performed with the aim to study thoroughly the heat and mass transfer in the system. Also, the electricity consumption by separate components has been evaluated during the tests.

As a result of specific experiments, accurate data of operating parameters have been obtained. First results show that some data of the pilot system components differ from their technical specification. Therefore, it has been important to check and update the data on the parameters and yields of the main system components: heat transfer coefficients of heat storages; heat transfer coefficient and yield of cooling machine; system *COP* and its dependence on the operating parameters.

The following data have been verified:

- Cold preparation
    - Heat rejection to the hot storage (preheating of tap water)
    - Heat rejection to the ambient through the outdoor unit
- Cold distribution
- Free cooling
    - For cold preparation only (charging of the cold storage tank)
    - With cold distribution through the ceilings
- Reverse mode
- HS discharge to DHW (use of DHW)
- HS discharge to the ambient through the outdoor unit
- Heat losses of the thermal storages
- Photovoltaic operation
- Autonomous PV-SAC operation

The PV-SAC operation has been improved in compliance with experimental results. Therefore, some of the tests have been performed several times. This proves the validity of the system model, which will be used in the following step of PV-SAC technology investigation.

4 SIMULATION OF PV-SAC MODEL

In the research, assessment of a solar air conditioning system has been performed. In particular, a design study has been carried out using Polysun® (Version 8) simulation software. A simplified schematic of the analysed system is shown in Fig. 4.1.

The reference system is located in Rapperswil (Switzerland). The global solar irradiation on a horizontal surface is $G_h = 1.103$ MW·h/m^2 per year. The irradiation on the PV module plane with southern orientation and a tilted angle of 15° is $G = 1.205$ MW·h/m^2 per year.

The specific annual DC yield of PV modules is almost 0.914 MW·h/kW$_n$ per year, and the overall AC energy production of the PV array is 2.344 MW·h per year. The 57.4 % proportion of the PV electricity is produced in a cooling season. The overall inverter efficiency during the year is 94.9 %. The DC electric energy losses of the DC lines are in the range of 36 kW·h per year.

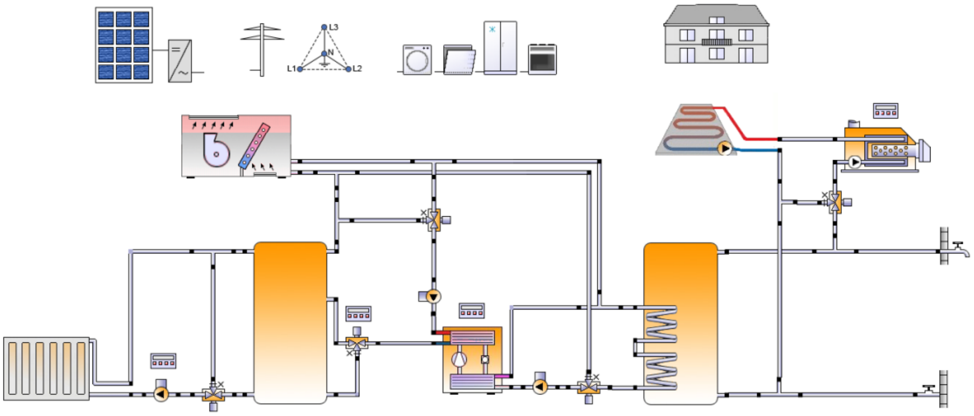


Fig. 4.1. Simplified schematic and illustrative elements of the PV SAC system

The cooling season is in the time from middle of May until the beginning of October. The specific cooling energy demand is $Q_{\mathrm{cool}} = 49$ kW·h/m^2 per year. In the cooling season, the building heat gain is approx. 13.9 MW·h, where the solar gain through the windows is 74.9 %, with 2 % stemming from the heat flow through the building envelope, 1 % – from natural ventilation and infiltration, and the rest 22 % is the internal heat gain obtained from building. In turn, when the outdoor temperature is lower than indoor temperature, a high proportion of 9.02 MW·h is rejected via the building envelope, natural ventilation and infiltration. The cooling system rejects 35.1 % of the building heat gain, 35.9 % is rejected by the building envelope, and 29 % is rejected by natural ventilation and infiltration. The building indoor average temperature during a cooling season is slightly lower than 22 °C most of the time, varying in the range of $T_{\mathrm{room}} = 17.5$ °C to $T_{\mathrm{room}} = 24.3$ °C.

Electricity is consumed to drive the heat pump, heat rejection unit andfluid pumps. The total electricity consumption in the cooling season is 1 040 MW·h, where 95.6 % is used to run the heat pump, 2 % – for the heat rejection unit and 2.4 % – for the pumps. The electricity consumption of system control is almost insignificant.

An average of 42 % of the PV produced electricity is used by the HP for cold production. The PV-SAC system produces 1.35 MW·h per year with the PV array, and 1.04 MW·h per year is consumed by all system electricity consumers in the cooling season. In this case, the PV-SAC system is able to fully provide itself with electricity. Moreover, 30 % of generated electricity could be stored in reserves. This means that a high potential of optimisation is hidden in the availability of the PV array electricity as well as in the low electric energy consumption for cold production.

A proportion of the waste energy from the heat pump is redirected to the hot storage for DHW. The use of this energy improves the system overall performance. For DHW needs, it suffices 1.29 MW·h per year of redirected heat, which is 99. 6% of heat demand plus heat losses.

The free cooling significantly improves performance of PV-SAC technology. The seasonal energy efficiency ratio (*SEER*) of free cooling is 23.51.

The *SEER* calculated by the following formula:

$$SEER_{\mathrm{el}} = \frac{\int(\dot{Q}_{\mathrm{H}}+\dot{Q}_{\mathrm{C}}+\dot{Q}_{\mathrm{DHW}}+\dot{Q}_{\mathrm{aux}}+\dot{Q}_{\mathrm{hl}})dt}{\int\sum(P_{\mathrm{el,PV-SAC}})dt}, \tag{4.1}$$

where gain of the system includes heat flow rates of heating ($\dot{Q}_{\mathrm{H}}$), cooling ($\dot{Q}_{\mathrm{C}}$), domestic hot water ($\dot{Q}_{\mathrm{DHW}}$), auxiliary heat source ($\dot{Q}_{\mathrm{aux}}$) and heat loses ($\dot{Q}_{\mathrm{hl}}$). The electricity consumption of the PV-SAC ($P_{\mathrm{el,PV\text{-}SAC}}$) consists of electrical power of heat pump ($P_{\mathrm{el,HP}}$), outdoor unit ($P_{\mathrm{el,OU}}$), hot side circulation pump ($P_{\mathrm{el,Hcp}}$), cold side circulation pump ($P_{\mathrm{el,Ccp}}$), cold distribution circulation pump ($P_{\mathrm{el,CCcp}}$), system control box($P_{\mathrm{el,A}}$) and each electrically driven valve ($P_{\mathrm{el,ev,}}$):

$$\sum(\mathrm{P}_{\mathrm{el,PV-SAC}}) = P_{\mathrm{el,HP}} + P_{\mathrm{el,OU}} + P_{\mathrm{el,Hcp}} + P_{\mathrm{el,Ccp}} + P_{\mathrm{el,CCcp}} + \\ + P_{\mathrm{el,A}} + \sum_{i=1}^{n}(P_{\mathrm{el,ev},i}). \tag{4.2}$$

The annual production of cooling machine together with free cooling is 4.954 MW·h of cold. Less than 1 % of generated cold is scattered in the technical room. The overall electrical *SEER* in the cooling season is 6.02. When the *SEER* of PV-SAC takes into account the cold production, the heat is redirected to DHW and free cooling. In this time, the total electricity consumption by the cooling machine and other electric-driven equipment is covered by the PV electricity.

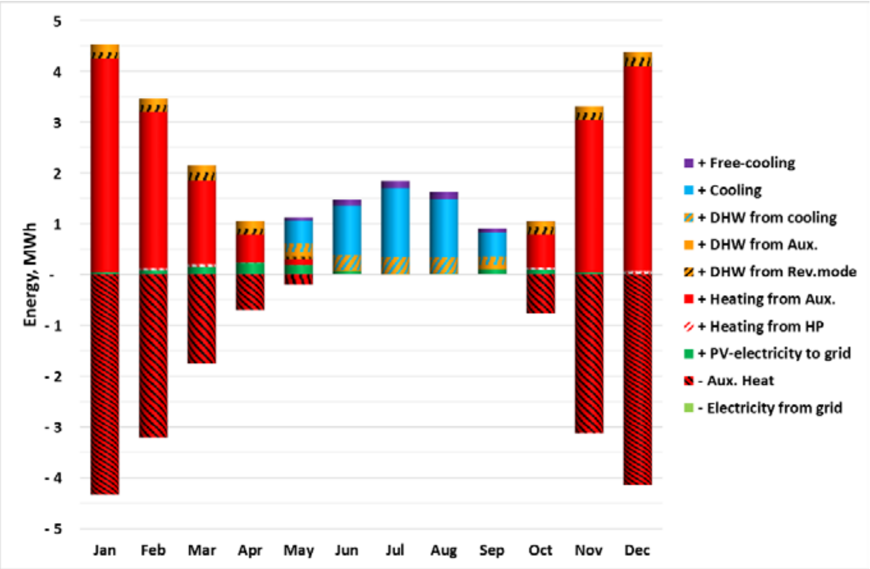


Fig. 4.2. Monthly energy flows in different operation of PV-SAC
*location of Rapperswil.

In percent, 42.6% of the PV electricity is produced in a non-cooling season and could be used for heating, e.g., employing the cooling machine as a heat pump or feeding into the public grid. As a result, 1.2 % of room heating demand and 57.7 % of DHW heating demand were covered by the PV-SAC system. The rest of heat should have been produced with a primary heat source.

High performance of reverse mode is achieved owing to the production of heat for the low-temperature heating. Reduced averaged temperature difference between the hot and the cold sides of HP significantly affects its coefficient of performance (*COP*). The effectiveness of heat production for domestic hot water is almost two times less than for low-temperature heating. Therefore, the production of heat for domestic hot water needs is of a second priority. The heat pump operates on the absorbed heat and consumed electricity after deduction of heat losses. In a non-cooling season, the *SEER* of HP is 4.8, which is lower than in a cooling season. Considering the above-mentioned facts, the annual electrical *SEER* of PV-SAC is 5.76.

The use of outdoor air heat is limited due to the freezing protection in the outdoor low temperature and high humidity conditions. Therefore, heating and DHW preheating are reduced in the time from November to March. This is the main disadvantage of the PV-SAC technology.

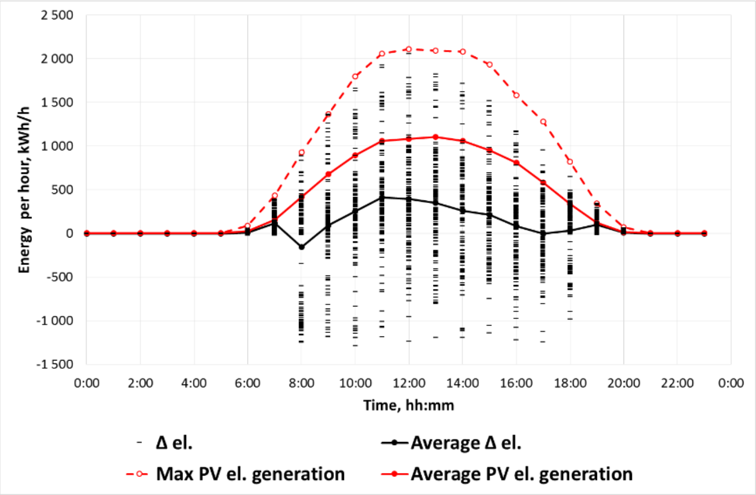


Fig. 4.3. PV electricity generation and consumption (-)/feeding (+) into the grid in the cooling season

*Δ electricity – the balance between the PV generated electricity, and the grid electricity consumption.

The ratio of the consumed electricity and the gains of PV-SAC system use is shown in Fig. 4.5. The data shown in this figure indicate that one of the technology targets is achieved: PV-SAC reduces the peak of electricity consumption from the grid for cold production.

The monitoring results show that considerable cooling consumption occurs at night. Hence, the cold storage needs recharging at the beginning of the day. Therefore, the electricity consumed by the cooling machine exceeds the PV generated electricity in the morning time.

Impact of System Enhancement

Within the framework of the Thesis, the system extension by adding sub-system components has been investigated as to their effect on the overall system performance. In all cases, the requirement is that the cooling demand should be covered in all type of systems. The base cooling system schematic consists of a cooling machine, cold ceilings and a heat rejection unit. Additional relevant components are added one by one until the reference system is reached. Table 4.1 presents the simulation results for all system versions.

Table 4.1

Results of Varying the System Type – Base System + Extension

System & extension	**CS**	**HT + DHW**	**Free-cooling**	**Reverse mode**	**Δ electricity (MW·h/a)**	**Cold generation (MW·h/a)**	**Heat + DHW (MW·h/a)**	**Annual electrical *SEER***
Base system (BS)	-	-	-	-	0.895	5.763	0	**3.98**
+ Cold Storage (CS)	X	-	-	-	1.393	4.545	0	**4.78**
+ Hot Storage (HS) and DHW	X	X	-	-	1.294	4.580	1.327	**5.63**
+ Free-cooling	X	X	X	-	1.306	4.956	1.291	**6.02**
+ Reverse mode (building with normal insulation)	X	X	X	X	1.040	4.945	2.580	**5.76**
Building with poor insulation	X	X	X	X	1.232	3.904	2.391	**5.66**
Building with highly efficient insulation	X	X	X	X	0.773	6.266	2.344	**5.90**

PV-SAC Operation in Different Climatic Conditions

With the reference to PV-SAC system template, simulations for other climatic zones have been performed. Most of the SAC systems are installed in European regions. Therefore, our simulations have been restricted to the regions under consideration. The system simulation and the energy analysis have been performed for three climatic zones with the reference cities: Cold Temperate, seaside – Riga (Latvia), 57° N; Hot Temperate, continental – Rapperswil (Switzerland), 47° N; Mediterranean, seaside – Almeria (Spain), 37° N.

In the cold-temperate (Riga) and the hot-temperate (Rapperswil) zones, a small cooling energy deficit is observed (see Fig. 4.4) and the room temperature exceeds 22 °C only a few days. An increase in the system power will reduce the *RT* peaks, while leading to irrationally low system *SEER* because the system operation time at nominal load occurs but seldom. Additionally, in the cold-temperate climatic zones, 1.3 to 1.6 times higher heating power is required. Low outdoor air temperature and low use of reverse mode improve the technology performance. In Riga, the electrical *SEER* of PV-SAC is 6.57.

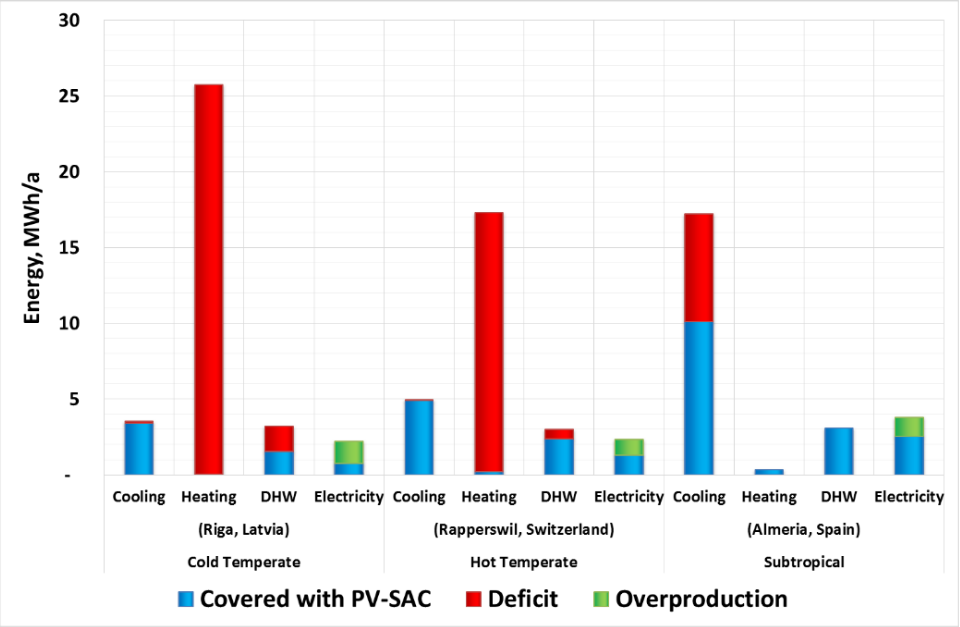


Fig. 4.4. PV-SAC annual demand and yields in different climatic zones

The system's reverse operation mode is almost not used in Almeria (subtropical zone). Air conditioning is needed there in all moths of the year. In the case of higher internal loads and external heat gains (solar, high outdoor temperatures), this rather small system will let the *RT* rise out of the comfort range. This will even aggravate the situation in a wet climate, when the system power of at least 2.7 times higher is necessary.

In Almeria the proportion of the total energy demand covered by PV-SAC system is higher than in other locations. This is due to several reasons. The first is a higher electricity production from the same size PV array due to a higher solar irradiance. The second is that the PV electricity production better matches the annual electricity demand. Finally, the third is a lower OFF time in the system because of freezing limitations. However, prolonged and incessant cold generation leads to overheating of the heat rejection tower. Moreover, a high outdoor temperature raises the heat rejection temperature. As a result, the cooling machine performance becomes worse. In Almeria, the electrical *SEER* of PV-SAC is 5.32.

Comparison of PV-SAC with Thermal SAC Technologies

The PV-SAC technology has been compared with two most widespread solar air conditioning technologies. Nowadays, a single-stage ABsorption thermal-driven chiller is commonly used. Closest followers of the market leader are ADsorption technologies.

ABsorption and ADsorption technologies are the thermal-driven ones, while the PV-SAC is driven electrically. Hence, the primary energy factor (*PEF*) is used to compare the yields of these technologies. Comparison of the primary energy consumption (conventional heating and cooling system included) is shown in Fig. 4.5. It is seen there that all SAC systems save primary energy, with the PV-SAC leading.

The *PEF*s reflect the reality of a complete energy system operation – from generation to the final consumption:

$$PEF_{\text{technology}} = PEF_{\text{heat,EUmix}} \int (\dot{Q}_{\text{H}} + \dot{Q}_{\text{C}} + \dot{Q}_{\text{DHW}} + \dot{Q}_{\text{aux}} + \dot{Q}_{\text{hl}})dt + $$

$$+PEF_{\text{el,EUmix}} \int \sum_{i=1}^{n} (P_{\text{el},i})\, dt, \tag{4.3}$$

where

$PEF_{\text{heat,EUmix}}$ – primary energy factor of heat, the Europe average in 2013;
$PEF_{\text{el,EUmix}}$ – primary energy factor of electricity, the Europe average in 2013;
$P_{\text{el},i}$ – electrical power of each electrically driven part of the system, W.

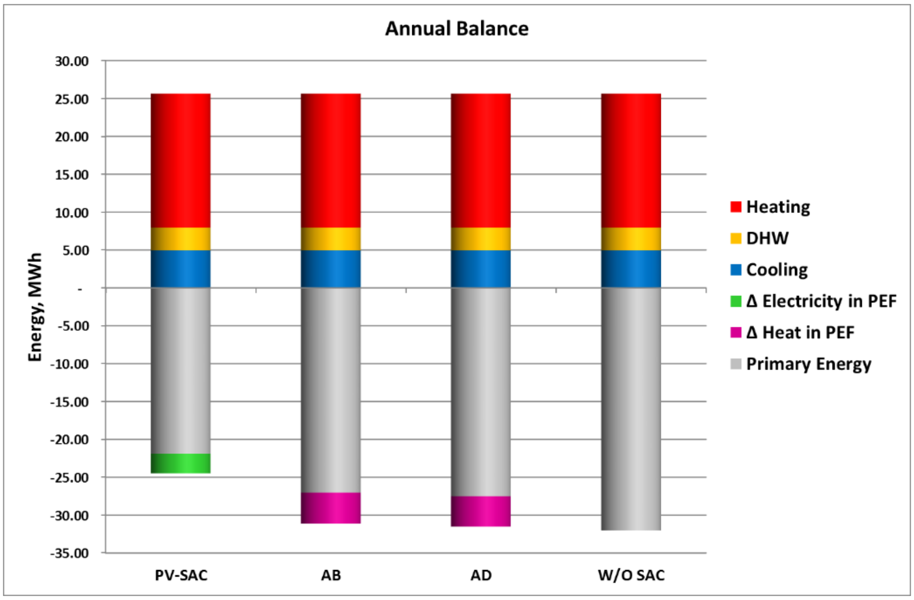


Fig. 4.5. Yield comparison of solar air conditioning technologies according to the primary energy factor

*Δ Electricity in *PEF* indicates the electricity overproduction, and Δ Heat in *PEF* – the heat overproduction regarding the primary energy factor.

Detailed investigation of the PV-driven, ADsorption and ABsorption solar air conditioning technologies has been performed. Advantages and disadvantages of all the three technologies have been considered from the perspective of system installation and operational experience, its operation monitoring, results of experiments under the critical operation conditions, results of long-term autonomous operation and simulation results.

The PV-SAC needs less solar irradiation for rejecting the same amount of heat from indoors. Less roof field for the solar absorption equipment is required by PV-SAC with the cooling power being equal. Moreover, PV-SAC components are more compact. Also, the thermal-driven cooling technologies need electricity for driving the outdoor unit, pumps, chiller and controlling equipment. This electricity amount is less as compared with that needed for the compressor evaporator based cooling technology; however, it is not covered by PV modules in a conventional set of thermal-driven cooling system. Besides, additional heat is required for thermal-driven chillers in the cases of insufficient heat from solar collectors. Increasing the solar collector field allows covering this gap. At the same time, this solution poses the overheating problems.

Thermal-driven SAC technology produces additional heat in a non-cooling season. This energy could be used for DHW preheating or even for covering partly the heating demand. Nevertheless, the existing data indicate that in the PV-SAC technology some electricity overproduction takes place. This extra electricity could also be used for household electricity needs.

Solar energy – as a renewable energy source – is available at the same time as room cooling is needed, and in this case a SAC system is a reasonable alternative to the systems using fossil fuel.

5 PV-SAC PERFORMANCE EVALUATION

The experimental results confirm the operability of PV-SAC technology. Additionally, the parameters of operation under critical conditions have been obtained. The experiments have shown appropriate functionality of the system at temperature and power fluctuations. Even in critical situations no failures of the system inside and outside components took place. Stable and predictable operation of the system has also been observed in the autonomous regime.

The simulation results show that the full cooling demand can be covered using PV-SAC technology in a standard single-family house. It has been found that PV power is sufficient for the maximum electricity consumption of the system. The results show that for effective use of PV-generated power the electricity accumulation is needed.

Financial Profitability Assessment

In the financial profitability assessment, the results for PV-SAC yield are used. In the reference building and under reference conditions the PV-SAC technology meets a cold demand of 5 MW·h per year and a heat demand of 2.6 MW·h per year. Additionally, 1 MW·h per year of electricity is generated.

The installation costs are highly variable due to several reasons. First, these costs depend on a particular location and building type. Second, they depend on the salary level in the engineering sectors in a particular region. Third, the costs of equipment to be installed are determined by its class. Future widespread applications of PV-SAC technologies would improve the workmanship, thus reducing the installation costs. In the financial profitability assessment, the estimated average costs of PV-SAC installation in European regions are applied.

Maintenance costs include periodical system check and adjustment. Brine should be replaced every 7 years of system operation. The lifetime of the main system part is 20 years. Three circulation pumps have a shorter lifetime: they should be replaced after 10 years. Respectively, the average maintenance costs are 87 Euro per year.

The financial profitability of PV-SAC is assessed in comparison with the conventional air conditioning (CAC). The PV overproduced electricity of up to 2.5 kW·h per day could be used for household needs; therefore, it is calculated as electricity saving.

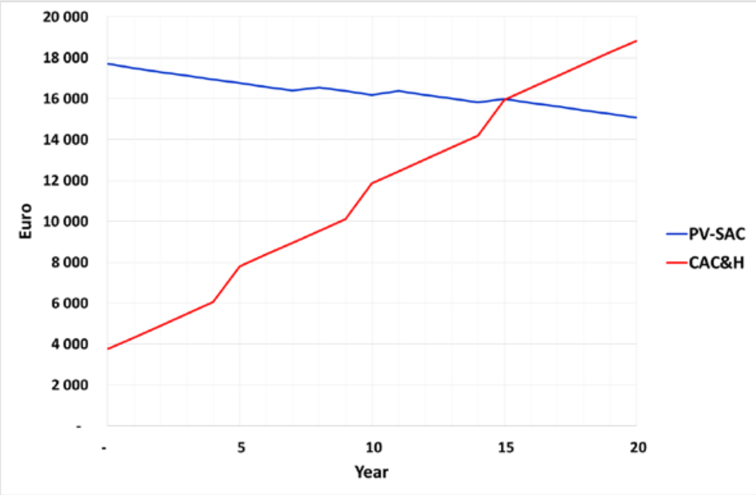


Fig. 5.1. Initial investment and maintenance costs
of PV-SAC and CAC&H technologies

Figure 5.1 shows that investment and maintenance costs of conventional technology will exceed the costs of PV-SAC technology after 15 years. The jumps of the curves show periodical replacement of system parts. The accounting rate of return of the project is 121.3 %. The results of work indicate that investment in PV-SAC technology is worth doing at the discount rate up to 2.36 %.

Environmental Impact

Energy generation and conversion always include environmental impacts. The use of PV-SAC technology promotes environment-friendly energy generation. Solar energy is a renewable, clean and predictable energy source, so it helps protect environment. Solar energy does not release carbon dioxide (CO_2), nitrogen oxides, sulfur dioxide, mercury, etc. into the atmosphere as it is done using many conventional heat and electricity sources. Not polluting the air, solar energy does not contribute to global warming, acid rains or smog.

The CO_2 content of atmosphere is one of the parameters for revealing the environmental impact of technology use. The potential of CO_2 reduction takes into account the CO_2 emission factor of the energy used. Therefore, substitution of solar energy for CO_2 producing (e.g., fossil) electricity sources reduces its emission into the air, thus reducing global warming.

The CO_2 calculation assumes that for heat generation the natural gas is used. The emission factor of stationary combustion heat (EF_{NG}) is 207.82 kg of CO_2 / MW·h.

The PV array generation is 2.344 MW·h per year, with an amount of electricity consumed for cold and heat generation and the rest fed into the grid. Overproduction of electricity is 1.04 MW·h per year. Conventional air conditioning consumes 1.652 MW·h per year of electricity for the same amount of cold generation. The auxiliary heat source in the CAC&H system consumes 219 kg per year of natural gas for heat generation equivalent to the evaluated technology. Respectively, the reduction in global GHG emission is 1835 kg of CO_2 per year.

As previously mentioned, the PV-SAC technology decreases CO_2 emission, at the same time increasing the comfort level in living rooms.

CONCLUSIONS

1. Based on the technical analysis presented, it is possible to integrate PV-SAC technology in the common HVAC engineering field. Currently, the PV electricity driven solar air conditioning systems are unavailable on the market, so no experience exists as to running such type of systems, despite the commercial availability of all PV-SAC components.

2. The pilot PV-SAC system has been developed and optimised in compliance with the pre-simulation results for a solar PV electric-driven compression chiller system. The conceptual definition of the PV-SAC and the analysis of working parameters have been presented.

3. The annual seasonal energy efficiency ratio (*SEER*) of transformation from the PV generated electricity into the useful cold and heat energy is found to be 5.76. A PV array generates more electricity than is consumed by the cold- and heat-production components of PV-SAC system in a long term. The PV-SAC technology fully covers the cooling demand of building under consideration.

4. In analysis of the system, its extensions by different components have been investigated as to their effect on the overall system performance. In particular, the PV-SAC system contains a cold storage (CS) to bridge the gap between the solar energy gain and the cooling demand. Besides, such CS reduces temperature fluctuations in the room. The implementation of heat rejection via domestic hot water preheating makes it possible to reuse 29 % of the rejected heat. The heat needed for DHW is completely covered by the compressor operation in a cooling season. With the insertion of CS and HS the cooling machine operation becomes closer to the optimum driving temperature range, which also improves the performance of cooling machine and, therefore, increases *SEER* of PV-SAC technology. The cooling demand is covered by 11 % through the use of free cooling in the time of low solar irradiation. In a non-cooling season, the cooling machine with the heat rejection unit is used as the heat source for DHW preheating. The results obtained indicate that for this purpose 7 % of heat demand is covered by the PV-SAC.

5. Comparison of PV-SAC technology with small-scale absorption and adsorption solar air conditioning technologies has shown that the PV-SAC needs less solar energy irradiation for rejecting the same amount of heat energy. Also, a smaller field of solar absorption equipment is required for a PV-SAC system, with the cooling power being the same. Moreover, indoor components of this system are more compact.

6. The results show that the system should be adapted to a particular location; also, the appropriate controller design is needed for high performance. The pilot PV-SAC system is able to completely meet the cooling demand in cold-temperate and hot-temperate climatic zones. At the same time, the results of PV-SAC experiments in Mediterranean climate zone evidence that a significant increase in the cooling power is necessary.

7. The investments and maintenance costs of conventional SAC technologies are expected to exceed those of PV-SAC technology after 15 years. Investment in the PV-SAC technology is worth doing at a discount rate up to 2.36 %.

The PV-SAC application promotes environment-friendly energy generation. PV-SAC technology reduces CO_2 emission without reducing the comfort level. Reduction of global greenhouse gas (CO_2) emissions is 1835 kg per year. This improves the air quality and promotes implementation of environment protection directives.

8. Considering all the previously mentioned information, the concept of enhanced technology of photovoltaic electrically driven compressor of cooling machine has a high potential for widespread application in the future.

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