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System design and feasibility of trigeneration systems with hybrid photovoltaic-thermal (PVT) collectors for zero energy office buildings in different climates

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ABSTRACT

Zero or plus energy office buildings must have very high building standards and require highly efficient energy supply systems due to space limitations for renewable installations. Conventional solar cooling systems use photovoltaic electricity or thermal energy to run either a compression-cooling machine or an absorption-cooling machine in order to produce cooling energy during daytime, while they use electricity from the grid for the nightly cooling energy demand. With a hybrid photovoltaic-thermal collector, electricity as well as thermal energy can be produced at the same time. These collectors can produce also cooling energy at nighttime by long-wave radiation exchange with the night sky and convection losses to the ambient air. Such a renewable trigeneration system offers new fields of applications. However, the technical, ecological and economical aspects of such systems are still largely unexplored.

In this work, the potential of a PVT system to heat and cool office buildings in three different climate zones is investigated. In the investigated system, PVT collectors act as a heat source and heat sink for a reversible heat pump. Due to the reduced electricity consumption (from the grid) for heat rejection, the overall efficiency and economics improve compared to a conventional solar cooling system using a reversible air-to-water heat pump as heat and cold source.

A parametric simulation study was carried out to evaluate the system design with different PVT surface areas and storage tank volumes to optimize the system for three different climate zones and for two different building standards. It is shown such a systems are technically feasible today. With a maximum utilization of PV electricity for heating, ventilation, air conditioning and other electricity demand such as lighting and plug loads, high solar fractions and primary energy savings can be achieved.

Annual costs for such a system are comparable to conventional solar thermal and solar electrical cooling systems. Nevertheless, the economic feasibility strongly depends on country specific energy prices and energy policy. However, even in countries without compensation schemes for energy produced by renewables, this system can still be economically viable today. It could be shown, that a specific system dimensioning can be found at each of the investigated locations worldwide for a valuable economic and ecological operation of an office building with PVT technologies in different system designs.

1. Introduction

Meeting the national and global energy targets and limiting the global temperature rise of 1.5 °C requires a change in all sectors. An electrification of heating and cooling systems and a massive increase of renewable electricity production is required. The building sector can contribute to the global targets by transforming the buildings into nearly zero energy buildings. A nearly zero-energy building should be built with an energy efficient construction which results in very low energy consumption. Additional energy for building operation should be generated from renewable sources produced on-site or nearby.

Space cooling and industrial refrigeration represent a significant

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Nomenclature

B	conversion factor for the conversion from primary energy to final energy, 647 g CO_2/kWh
η_0	optical efficiency
η_{ST}	thermal conversion efficiency of a solar thermal module
η_{PV}	electrical conversion efficiency of a PV module
τ	service lifetime of the energy system
$\tau_{payback}$	the payback time of the system
A_{N0}	annuity of the capital-related costs
a_a	annuity factor
C_I	investment costs
$C_{a,total}$	total yearly costs, with indices *PVT* for the PVT system and *ref.* for the reference system
$C_{a,main.}$	costs for maintenance of the system
$C_{a,c}$	yearly operational costs
ΔC_a	annual cost savings
$C_{PE,save}$	costs for primary energy (PE) savings
$CO_{2,PVT}$	CO_2 emissions caused by the PVT system
$CO_{2,ref.}$	CO_2 emissions caused by the reference system
$CO_{2,save}$	saved CO_2, difference between reference system and investigated system
E	specific electrical energy demand from a system
PE	primary energy
PE_{PVT}	primary energy from the investigated PVT system
$PE_{ref.}$	primary energy required by the reference system
PE_{save}	saved primary energy
$PEF_{el.}$	primary energy factor (PEF) of 2.4
$\dot{Q}_{cplg,i}$	gains due to air flow between two zones
$\dot{Q}_{g,c,i}$	internal convective gains by people, equipment, illumination, etc.
$\dot{Q}_{ISHCCI,i}$	absorbed solar radiation on all internal shadings
$\dot{Q}_i$	convective heat flux to air node
$\dot{Q}_{inf,i}$	infiltration gains
$\dot{Q}_{solair,i}$	fraction of solar gains to the air node
$\dot{Q}_{surf,i}$	convective gain from building surfaces
$\dot{Q}_{vent,i}$	ventilation gains
q	interest rate

Abbreviations

CC	compression chiller
COP	coefficient of performance
DHW	domestic hot water
EER	energy efficiency ratio
rev. HP	reversible heat pump
PE	primary energy
PEF	primary energy factor
PV	photovoltaic
PVT	photovoltaic-thermal collectors
ST	solar thermal

share of the worldś energy consumption. The use of energy for space cooling has more than tripled between 1990 and 2016. It was responsible for about 21,000 TWh or 10% of the global electricity consumption in all sectors in 2016 (International Energy Agency, 2018). In Germany with moderate summer climate, the national net electricity consumption in 2008 was 524 TWh, of which 71 TWh (14%) were used for refrigeration purposes (Umweltbundesamt, 25/2014). 11 TWh were related solely to residential space cooling. The global demand for residential air conditioning alone is estimated to jump by about a factor of 13, namely from 300 TWh/a in the year 2000 to 4000 TWh/a in 2050, with the majority of growth in developing countries (Isaac and van Vuuren, 2009). Some of the reasons for the increase are the anthropogenic climate change, an increasing living standard, the growing population mainly in hot climates, higher internal thermal loads in buildings and architectural trends like glass facades.

The conventional technology for air-conditioning and refrigeration is still the electric compression chiller (CC) with peak loads during midday (Balaras et al., 2007; Desideri et al., 2009). To increase the renewable energy shares in cooling and heating systems, thermally driven technologies supplied with solar heat and conventional CC supplied PV electricity can be used (Eicker and Pietruschka, 2009; Fong et al., 2010; Bilgili, 2011; Hartmann et al., 2011; Henning and Döll, 2012; Otanicar et al., 2012; Buonomano et al., 2013; Lazzarin, 2014). Advanced technologies are diffusion absorption cooling machines, without pumps in the refrigerant cycle (Jakob et al., 2008; Yousfi et al., 2017), or water steam jet ejector chillers (Pollerberg et al., 2012; Joemann et al., 2016). Today PV cooling systems usually have an economic advantage over thermally driven systems in non-residential buildings, while their primary energy (PE) savings are comparable (Hartmann et al., 2011; Henning and Döll, 2012; Otanicar et al., 2012; Lazzarin, 2014; Eicker et al., 2015). Also combinations of photovoltaic-thermal systems (PVT) and desiccant cooling technologies were investigated, but they are not competitive (Guo et al., 2017).

In the 1970s, research started to investigate hybrid PVT collector systems (Hendrie, 1979; Johnson, 1983; Cox and Raghuraman, 1985; Lalović et al., 1986; Garg et al., 1990; Hayakashi et al., 1990). Lalović et al. (1986) constructed a glazed insulated water based PVT collector in 1986 with an optical efficiency η_0 of 0.52. In 1989 Hayakashi et al. (1990) designed a collector whose η_0 reached 0.65 with a similar construction. Garg et al. (1990) manufactured a thermosiphon application in the same year. Reviews of liquid (Zondag, 2008; Michael et al., 2015) or air-based (Zondag, 2008; Kumar and Rosen, 2011; Michael et al., 2015) flat plate solar collectors as well as concentrating collectors (Ju et al., 2017) or all types (Charalambous et al., 2007; Chow, 2010; Riffat and Cuce, 2011; Wu et al., 2017) can be found.

A detailed literature review of different types of PVT collectors is given in (Kumar et al., 2015). PVT systems need less collector area than separate side-by-side systems (Chow, 2010; Riffat and Cuce, 2011). The performance of hybrid PVT systems strongly depends on the climatic boundary conditions, the system components as well as the operational design (Zondag, 2008; Chow, 2010; Riffat and Cuce, 2011). The technical performance of solar conversion into heat and electricity was studied in a variety of articles via experiments and simulations of different collectors (Bergene and Løvvik, 1995; Huang et al., 2001; Sandnes and Rekstad, 2002; Tripanagnostopoulos et al., 2002; Zondag et al., 2003; Kalogirou and Tripanagnostopoulos, 2006; Tripanagnostopoulos, 2007; Dupeyrat et al., 2011; Saghafifar and Gadalla, 2016). A ST collector has a greater thermal efficiency than a comparable PVT collector (Buonomano et al., 2016), since the heat losses are reduced by a transparent cover and low emittance coatings. If night cooling is considered, the long wave emittance needs to be high, which leads to higher daytime heat losses.

Also optical efficiencies of PVT collectors tend to be lower than those of ST flat plate collectors, with approximately 80% (Dupeyrat et al., 2011). However, this disadvantage can be compensated by the PVT electricity production. Due to the fact of decreasing electricity production with increasing PV cell temperatures, the collector and operational design of PVT systems can affect the electrical yield, whether positively or negatively (Zondag, 2008). For uncovered PVT collectors the electrical yield can increase up to 5% (Zondag et al., 2003; Herrando et al., 2014; Palla et al., 2014; Buonomano et al., 2016), while it decreases in covered PVT collectors due to the higher cell temperatures and optical losses compared to conventional and comparable PV modules (Tripanagnostopoulos et al., 2002; Zondag et al., 2003;

Zondag, 2008; Buonomano et al., 2016). For nine different collector design concepts with water based PVT collectors in optimal orientation, the annual average thermal and electrical conversion efficiencies (η_{ST}, η_{PV}) could be measured in a range from 24 to 39% and 5.8 to 7.6%, respectively (Zondag et al., 2003).

When PVT collectors are compared to PV- or ST-collectors, the comparison of component parameters and the construction is crucial for the evaluation of the annual performance. In a study for a well-insulated residential building in Scandinavia, the performance of a PV- and ST-system was compared to PVT systems for heating, domestic hot water (DHW) and electricity production. A PV-only system performed the best and resulted in nearly zero energy performance of the building, as the electrical efficiency of the PVT system was 3–8% lower than the PV system (Good et al., 2015).

The PVT market developed in the last ten years from 10 manufacturers with 33 commercial standard products of PVT-collectors in 2008 (Hansen and Sorensen, 2006) into multiple types of panels that are commercially available from approximately 33 manufacturers worldwide in 2015 (Cremers et al., 2016).

The effect of infrared longwave losses towards the night sky is called radiative cooling and can be used to generate cooling energy at night. Research goes back to 1977 (Bartoli et al., 1977) and it has been a topic over the last 40 years (Al-Nimr et al., 1998). The achievable thermal cooling power strongly depends on the effective nocturnal sky temperature. At clear sky conditions, the longwave irradiance can reach over 300 W/m^2 (Iziomon et al., 2003). Average experimental cooling capacities during nocturnal operation are in a range of 30–60 W/m^2 for water-based PVT technologies (Erell and Etzion, 2000; Dimoudi and Androutsopoulos, 2006; Eicker and Dalibard, 2011; Lu et al., 2016). As part of the Solar Decathlon competition in 2010, a system was designed in the “home+” zero energy building which uses water based PVT collectors as energy source for a reversible heat pump for the building’s heating and cooling energy demand. For this system a specific cooling power between 60 and 65 W/m^2, with a temperature difference between inlet and outlet of 2.9–4.5 K, could be measured in Stuttgart, Germany (Eicker and Dalibard, 2011). As PVT systems are still not widely used, there are few systematic publications on their performance, feasibility, and economic benefits.

This paper shows the applicability of PVT collectors as a heat source and heat sink for a reversible heat pump (rev. HP) in three different climate and regulatory conditions and analyzes the technical, economic and ecological aspects through dynamic simulations with the simulation software TRNSYS. Parameters for the PVT collectors, such as optical efficiency and wind dependent heat loss coefficients or emittance, were derived from measurements of a PVT outdoor test stand. Other parameters like U-values of the building or efficiency of the heat pump were taken from literature or relevant standards. As PVT systems have the capability to produce electricity, heat and cold, applications like office buildings, where all the three energy forms are needed, offer the most suitable application from an economic and ecological perspective.

Section 2 shows the methodology applied in this research and how the simulation model for this study was set up. The most important/interesting simulation results are presented and analyzed in (Section 3), followed by a summarizing discussion on the spot for the full results from a technical, economic and ecological perspective. Finally, Section 4 (conclusion) summarizes the main outcomes and remarks of the work conducted in this research. The conclusion also contains an outlook on the topic “trigeneration systems” and recommendations for future research work.

2. Methodology

The full potential of PVT systems can only be utilized, when applications that require electricity, heat and cold exist. Non-residential buildings such as office buildings, shopping malls or data centers offer optimal boundary conditions for PVT systems. Therefore, this study examines the overall performance of a PVT-system design for a typical office building in comparison to a reference system with an air-to-water heat pump. In a parametric study, the influences of different PVT surface areas and thermal storage tank volumes are investigated. Furthermore, the technical, economic and ecological potentials of PVT integration into the building’s HVAC system is analyzed. Table 1 summarizes the examined scenarios in which the locations, building standards and the building energy system were varied.

2.1. Locations and corresponding climate zones

In order to investigate the climatic influence on the system performance, three different climatic zones were chosen. The climate of Moscow represents cold climate zones, where heating energy demand dominates. In winter, the temperature can drop to −25 °C or even below and in summer the temperatures can rise up to 30 °C. Short transitional periods between cold and warm periods are also typical for this climate zone. The moderate central Europe climate is represented by the climate of Stuttgart. In this zone the temperature is more balanced. The winter is less extreme and the transitional periods in spring and autumn are longer with mostly mild weather conditions. In this climate the energy demand for heating also dominates. Dubai represents the hot desert climate with a yearly average temperature of 28.4 °C. For this analysis the weather data in hourly resolutions were taken from the software Meteonorm in the TMY2 format (Meteotest, 2014).

2.2. Building model and corresponding building standards

In the present work, an office building and the heating and cooling air-conditioning system were modelled using the simulation software TRNSYS (version 17.2). Office buildings can be classified in different ways as presented in (Brown et al., 2000) and (Steadman et al., 2000). For the simulation in TRNSYS, all relevant data such as geometry, envelope, glazing type and window to wall ratio, usage profiles and internal gains were provided in order to fully model the building. The dimensioning of the office building was based on the recommendation of IEA SHC Task 38 (IEA SHC, 2009).

Fig. 1 shows the geometry of the building model and Table 2 presents the parameters of the building geometry.

Since PVT systems can be an interesting solution for both new and existing buildings, two different building standards were examined. The building’s layer structure and the resulting U-values of the individual components are listed in Table 3. Standard 1, the passive house or low-energy house, has a highly insulated building envelope with active and passive measures for air conditioning such as heat recovery. On the other hand, the building standard 2 represents a typical building stock. It has a heat demand of about 45–60 kWh/(m^{2}a), which is a typical

Table 1
Methodological overview on the parameter variation of the investigated scenarios.

Location and climate zones	Building standard	Building energy system
(a) Moscow, Russia: Cold climate (b) Stuttgart, Germany: moderate climate, central Europe (c) Dubai, United Arab Emirates: Hot climate, desert near the sea	(a) Passive house (standard 1) (b) Conventional - according to IEA Task 32 (standard 2)	(a) Reference (air-to-water heat pump) (b) PVT and rev. HP

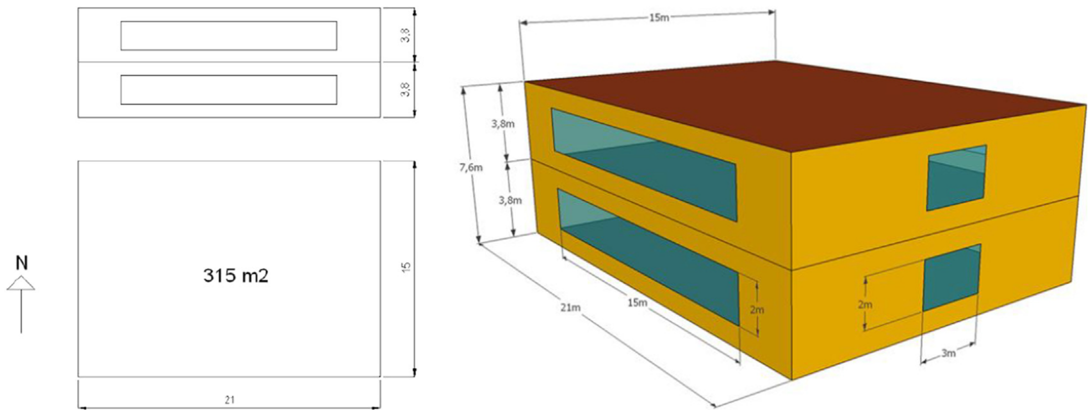

Fig. 1. Floor plan and north-south view of the building model based on the IEA Task 38 (left) and 3D model (right).

Table 2
Building geometry parameters.

Parameter	Value	Unit
Storey/thermal zones	2	–
Total gross floor area	630 (L × W × H = 21 × 15 × 7.6 m)	m^2
Gross/net floor height	3.8/3.2 m	m
Net area per floor	273.6	m^2
Total air volume	1 751	m^3
Modelled building orientation	Along the east-west axis, oriented to south	–
Glazing ratio for the north and south facades	38	%
Glazing ratio for the east facade	10	%
West facade opaque	0	%

Table 3
Building envelope specifications for standard 1 (passive house) and standard 2 (existing building).

Component	U-values in W/(m^2K) and g-values (–)	
	Passive house (standard 1)	Building stock (standard 2)
Exterior wall	0.148	0.345
Windows (g-value)	0.8 (0.5)	1.4 (0.62)
Ground floor	0.15	0.353
Roof	0.148	0.315

value for buildings that were built between 1995 and 2001. The building standard of the existing building is based on the IEA SHC task 32 (IEA SHC, 2007).

According to the German standard VDI 2067-10 there is a general requirement for air exchange in buildings of 0.5 1/h during occupancy (VDI, 2013). Outside the period of use, the German standard DIN V 18599-10 requires a basic air exchange of 0.05 1/h (DIN, 2018). By definition of the passive house standard, the usage of ventilation systems with heat recovery is necessary. At least 75% of the extracted heat from exhaust air has to be recovered. Therefore, a ventilation with heat recovery is implemented with an air exchange rate of 0.45 1/h during occupancy. For an optimized building performance of the passive house an external shading system is implemented according to the German standard DIN 4108-2 (DIN, 2013). The shading is automatically activated with the incoming solar radiation on the respective surfaces when exceeding 200 W/m^2 and is deactivated again below 180 W/m^2. During the heating season, the external shading is deactivated to utilize maximum solar gains.

The control of the heat recovery is continuous in the heating case, whereas in the case of cooling it automatically switches on when the outside air temperature exceeds the cooling set-point temperature of the room. Heating and cooling of the building takes place through a thermally activated ceiling. The inlet temperature (T_{in}) is regulated to 32 °C (32/28 °C) in the heating mode and to 18 °C in the case of cooling.

2.2.1. Building internal loads

Internal loads are calculated according to the German standard DIN V 18599-10 with an assumption of 15 persons during occupancy periods. The heat dissipation per person is calculated with 70 W and an additional specific load of 7 W/m2 for electrical devices (such as PC's) and lighting during occupancy. Since self-consumption of PV-electricity leads to cost savings, the electricity demand for office building utilities, appliances and server are calculated according to the Swiss guideline SIA 380/4 ("Electrical Energy in Building Construction") (SIA, 2011). The power consumption of electrical devices is 33.4 kWh/(m^2a) with a specific power of 3.8 W/m^2 and a total demand of 21 017 kWh/a. At night and weekends, it was assumed that the consumption is reduced to 20%. Domestic hot water consumption is not considered for the office building in this study.

2.3. Building energy systems

In order to evaluate the added-value of the proposed system design, the proposed PVT system with a reversible heat pump is compared to a reference system which implements an air-to-water heat pump. Each system is described in the following sub-sections.

Table 4
Simulated heating and cooling energy demands for the two building standards at the three different climates.

	Unit	Moscow		Stuttgart		Dubai	
		Passive	Stock	Passive	Stock	Passive	Stock
Specific heating energy demand	kWh/m^2a	29	78	14	44	0	0
Specific cooling energy demand	kWh/m^2a	8.5	10.4	8.5	10.2	82	129
Peak load heating	kW	10.2	26.1	6.4	17.3	0.2	0.3
Peak load cooling	kW	9.2	12.8	8.8	11.5	12.9	21.2

2.3.1. The reference system

The reference system is used as a comparative model for load calculations, to calculate payback times, heat and cold production costs and PE balances in comparison to the proposed PVT systems. The heating and cooling energy demands are calculated by setting a constant room temperature in winter of 20 °C and in summer of 26 °C. In the simulation, a system with unlimited power was considered for such calculations, i.e. ideal heating/cooling energy demands. The electrical energy demand for heating and cooling by a reversible air-to-water heat pump is calculated with a fixed coefficient of performance (COP) according to the funding criteria of German Federal Office for Economic Affairs and Export Control (BAFA). The COP of air-to-water heat pumps has to be at least 3.1 in operating point A2/W35. Additional energy demand for heat rejection in heat pump systems of 30% of the total electrical energy consumption is also taken into account for the reference cooling system (Eicker et al., 2015). The electrical energy demand is drawn from the grid. The heating and cooling energy demands as well as the peak loads of all building standards and locations are shown in Table 4.

The calculation of the building energy demand for heating and cooling is based on the following balance equation (TRNSYS 17, 2018).

$$\dot{Q}_i = \dot{Q}_{surf,i} + \dot{Q}_{inf,i} + \dot{Q}_{vent,i} + \dot{Q}_{cplg,i} + \dot{Q}_{g,c,i} + \dot{Q}_{solair,i} + \dot{Q}_{ISHCCI,i} \tag{1}$$

where $\dot{Q}_i$ is the convective heat flux to air node (power required by the HVAC system to keep the room at the set point temperature), $\dot{Q}_{surf,i}$ is the convective gain from building surfaces, $\dot{Q}_{inf,i}$ is the infiltration gains, $\dot{Q}_{vent,i}$ is the ventilation gains, $\dot{Q}_{g,c,i}$ is the internal convective gains by people, equipment, illumination, etc., $\dot{Q}_{cplg,i}$ is the gains due to air flow between two zones, $\dot{Q}_{solair,i}$ is the fraction of solar gains to the air node and $\dot{Q}_{ISHCCI,i}$ is the absorbed solar radiation on all internal shadings.

2.3.2. PVT system

The potential of solar heat pump systems was in the focus of many research projects, such as IEA SHC Task 44, UMSys, BiSolar-WP, GeoSolar-WP, PVT-Norm and PVT HeatCool. The results presented in this paper were obtained within the project PVT HeatCool. The system used PVT collectors for direct heating and cooling the office building described in Section 2.2. Due to the design of uncovered PVT collectors, the achievable temperature level for heating applications was low compared to conventional solar collectors.

The aim of this study was to investigate the potential of PVT collectors that are used as a heat and cold source for a rev. HP in combination with a thermal storage. Fig. 2 shows the hydraulic scheme of the system for an operation in the cooling mode on summer nights (top) and in the heating mode in winter (bottom). The system is designed to be used during the whole year, in summer to provide cold and in winter for heating. The thermal storage acts as a central unit. To avoid any problem in stratification in the storage, the mass flow direction in summer and winter has to be switched. Therefore, the storage has two internal heat exchangers, the one on the top is used for cooling and the

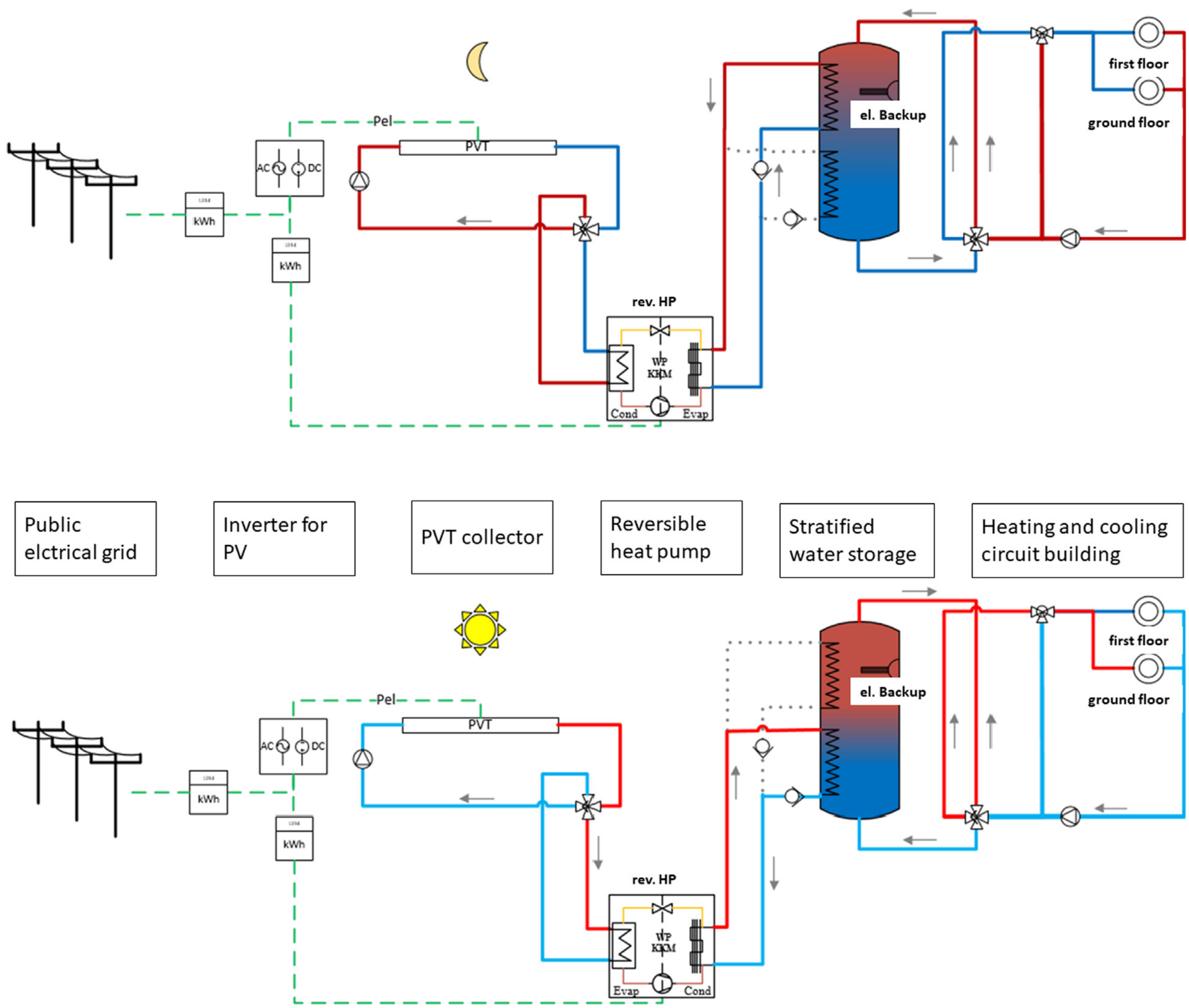

Fig. 2. Hydraulic scheme of the PVT system, operation mode cooling in summer at night-times (top) and heating in winter during day-times (bottom).

one at the bottom for heating.

The hydraulic circuits of the PVT collectors and the HP (left side of the storage) are filled with a 33% water/ethylene glycol mixture whereas the hydraulic circuit of the building's heating and cooling system is filled with water for the storage tank and the thermally activated ceiling (right side of the storage).

Systems control algorithm (summer and winter): In summer (cooling mode) during the night, heat is removed from the PVT system by long-wave radiation between the collectors surface and the night sky, in addition to the convective heat transfer caused by the temperature difference to the mean temperature of the collectors surface and ambient. Ideally, the storage tank can be sufficiently cooled during the night to cover the daily cooling loads of the building. The PVT circuit switches into operation when the global radiation is less or equal to 180 W/m^2. The rev. HP operates as a chiller and uses the PVT collectors as a heat sink (cold source) to reject the heat from the storage tank. The chiller works until the temperature at the bottom (0.1 × storage height) of the storage tank is 10 °C. To fulfill the comfort criteria in the building, the storage must be able to store enough cold during the night-time to air-condition the building during the day. A backup system is not taken into account, since the chillers are designed to the maximum load at each location. In the heating mode, the thermal energy harnessed by the PVT collectors during the day is used as the heat source for the HP. When the storage is fully charged by the HP, the system switches off. An electrical heating element serves as a backup system. To use as much energy as possible form the collector field, the signal for the heating element is triggered only when the outside temperature is below −10 °C or the room temperature falls below the comfort level. Fig. 3 shows the developed simulation model of the system in TRNSYS including all components (types) used for the required system operation. The developed model allows a detailed analysis of the behavior of the system from a technical, economic and ecological perspective.

2.4. Economic and ecological analysis and framework conditions

For the ecological performance assessment, the conversion of electricity into PE was calculated with the current German power mix with a primary energy factor ($PEF_{el.}$) of 2.4 for electricity. The CO_2 emissions and savings are calculated with a CO_2-equivalent for the German power mix of 647 g CO_2/kWh_{final} (β) by GEMIS (GEMIS). The GEMIS conversion factor for the conversion of PE to final energy for electricity is 2.99 kWh_{PE}/kWh_{final}.CO_2 savings are calculated as savings compared to the reference system.

$$PE = E \times PEF_{el.} \tag{2}$$

$$PE_{save} = PE_{PVT} - PE_{ref.} \tag{3}$$

where PE is the primary energy form a system, E is the specific electrical energy demand from a system, PE_{save} is the saved primary energy, PE_{PVT} is the primary energy from the investigated system and $PE_{ref.}$ is the required primary energy by the reference system.

$$CO_{2,ref.} = \frac{PE}{2,99} * \beta \tag{4}$$

$$CO_{2,save} = CO_{2,ref.} - CO_{2,PVT} \tag{5}$$

where $CO_{2,ref.}$ is the CO_2 emissions by the reference system, β is the conversion factor to CO_2 emissions for the conversion from primary energy to final energy and $CO_{2,save}$ is the saved CO_2 emissions. The economic analysis and performance comparison of the two systems were carried out on the basis of the equivalent annual cost method according to the German Guideline VDI-2067. This method summarizes one-time investment (annuity of the capital-related costs), operation and maintenance costs as well as the costs for planning and installation (VDI, 2013). The annual costs were calculated based on a constant annuity. For simplification, a mean service lifetime of the components of 20 years was considered and an interest rate of 4.5% was assumed.

$$AN_0 = \sum C_I * a_a \tag{6}$$

$$a_a = \frac{q-1}{1-q^{-\tau}} \tag{7}$$

$$C_{a,total} = AN_0 + \sum C_{a,main.} + \sum C_{a,c} \tag{8}$$

where AN_0 is the annuity of the capital-related costs, C_I are the investment costs, a_a is the annuity factor, q is the interest rate, τ is the service lifetime of the energy system, $C_{a,total}$ is the total yearly costs, $C_{a,main.}$ is the costs for maintenance and $C_{a,c}$ is the yearly operational costs.

Annual cost savings are calculated as the difference between the

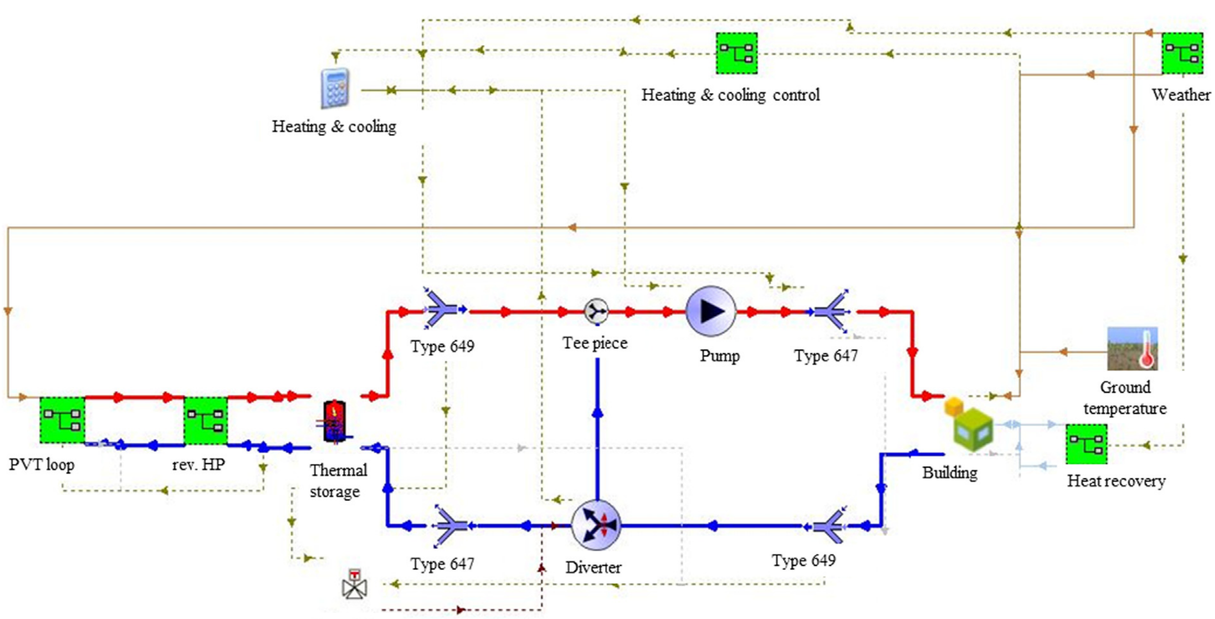

Fig. 3. TRNSYS simulation model of the system.

annual cost of the PVT system and the reference system. Payback times are calculated as additional investment costs compared to the reference system relative to the savings of operation and maintenance costs of the PVT system. As an economic and ecological indicator of the different systems, costs for PE savings are calculated as the ratio of the annual cost difference and the primary energy savings from the PVT system and the reference system. Specific system costs are given as an indication of the cost of the heating and cooling system per unit of heat pump capacity, as well as the specific costs for heating and cooling energy production.

$$\Delta C_a = C_{a,total,PVT} - C_{a,total,ref.} \tag{9}$$

$$\tau_{payback} = \frac{C_I - C_{I,ref}}{(C_{a,main,ref.} + C_{a,c,ref}) - (C_{a,main,PVT} + C_{a,c,PVT})} \tag{10}$$

$$C_{PE,save} = \frac{\Delta C_a}{PE_{save}} \tag{11}$$

where ΔC_a is the annual cost saving, $C_{a,total,PVT}$ is the total yearly costs of the PVT system, $C_{a,total,ref.}$ is the total yearly costs of the reference system, $\tau_{payback}$ is the payback time of the system and $C_{PE,save}$ is the costs for PE savings. In the economic analysis, specific price assumptions are based on empirical values from completed projects, invoices from manufactures and cost assumptions from literature. The cost assumptions are shown in Table 5. Maintenance costs for the technical components of the systems can be calculated as percentages of the investment costs C_I (Henning, 2004).

To obtain a realistic view on the economics in the three different countries, annual electricity costs and electricity related cost savings are calculated based on assumptions of country-specific energy prices and an energy price increase of 3% p.a. according to the VDI 2067standard (VDI, 2013). Annual electricity costs are calculated using average electricity prices (see Table 6). Electricity in Dubai is subsidized by the state. The electricity price for residential and commercial customers in Dubai depends on the total yearly energy consumption and is grouped into four categories (DEWA, 2018). For the office building considered in this study, a price of 0.28 Dirham per kWh can be applied, which is equivalent to a price of approximately 0.067 €/kWh. Since March 2015, companies, public institutions and residents have been allowed to install solar roof panels (PV) in Dubai. The excess electricity production will be fed into the national grid through the connection to the Dubai Electricity & Water Authority (DEWA) network. A clear feed-in-tariff model for electricity into the grid does not exist yet, but is expected for the near future. In Russia, electricity prices vary widely between regions. For 2012, the electricity price in Moscow for industry was 2.49 RUB/kWh (0.062 €/kWh) and for private end-consumers was at 3.80 RUB/kWh (0.09 €/kWh) (AHK, 2013). The end-user tariff was chosen for the calculation of energy costs for the office building in this study. In Germany, the electricity price depends on the electricity consumption. Up to a demand of 5 000 kWh per year, an average for the specific electricity price of 0.294 €/kWh can be assumed (Destatis, 2018)

Table 6
Prices for electricity and an energy price increase over 20 years.

Location	Energy prices and energy price over 20 years with an increase of 3% p.a		Source
Stuttgart	0.294 (0.395)	€/kWh	(Destatis, 2018)
Moscow	0.090 (0.121)	€/kWh	(AHK, 2013)
Dubai	0.067 (0.090)	€/kWh	(DEWA, 2018)

A monetary compensation for electricity for Germany is taken into account, which is based on the regulations of the national renewable energy law (EEG). There are currently no compensation models in Dubai and Moscow, so no compensation for excess electricity has been considered for them.

3. Results

The overall simulation-based performance of the proposed PVT system was technically and economically analyzed and compared to the reference system. The electricity requirement for building operation is considered to be same for both systems. Firstly, a parametric study was done to optimize the system design. At each location for the two different building standards, different PVT surface areas (10, 25, 50, 75, 100, 125 and 150 m^2) and storage tank volumes (1, 2, 4, 8, 12, 20 m^3) were varied.

3.1. System technical behaviour

Based on the parametric runs, the simulation results are plotted in this section only for the best configuration at the three locations for the passive house standard for the summer operation to understand the dynamic behaviour of the system. The summer case is shown as the more critical operation mode for such a system. (In Figs. 4–6) the electricity requirement for building operation in summer is shown as a red area, and the electricity requirement for system operation (PVT, HP and pumps) as a blue area. This clearly shows the control strategy, where the refrigeration system is mainly in operation at night to make the most efficient use of radiative cooling. Only under extreme conditions, the system has to be operated for a few hours during the day time. The electricity production from the PV field is shown as black lines on the figures. Different representative PV areas are plotted by different line types.

At all locations the smallest PVT field of 10 m^2 covers only a small part of the electricity demand for the building's operation, even on those days with the highest radiation levels. With a collector field of 75 m^2 only small parts of the electricity requirement for building operation cannot be covered in the morning and evening hours for Stuttgart and Dubai. In Moscow, on the other hand, even with an area of 100 m^2 a complete coverage with renewable energy for building and system operation over a longer period is not possible. The room temperature exceeds only in a few moments the set point temperature of

Table 5
Specific cost assumptions for the components and calculations.

Specific costs	Value	Unit	Source
PVT collectors (mean value of the collector type examined)	225	€/m^2	Invoices to authors
PV inverter	350	€/kW	Invoices to authors
Reversible heat pump	800	€/kW_{th}	(Tjarko, 2013)
Thermal storage	470	€/m^3	Empirical value
Pumps	800	€	(Eicker and Pietruschka, 2009; Cardinale et al., 2010)
Installation, Hydraulics + PV (for the PVT system)	40	% v. C_I	Empirical value
Maintenance (PVT system)	1.5	% v. C_I	(Henning, 2004)
Costs for planning	5	% v. C_I	(Henning, 2004; Eicker and Pietruschka, 2009)
Interest rate	4.5	%	
Measuring and control equipment	5 000	€	(Henning, 2004)

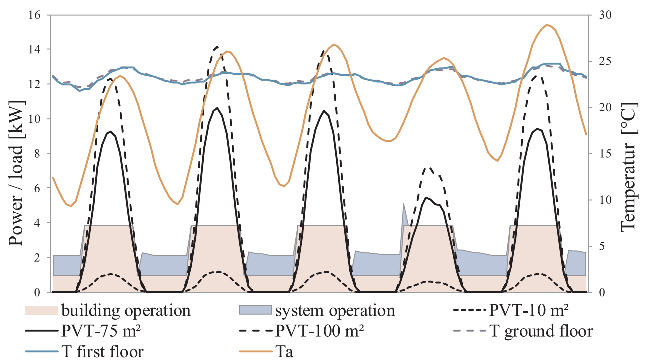

Fig. 4. System behaviour for 5 hot summer days in Stuttgart passive building, storage tank V = 1 m^3 and three representative PVT collector areas.

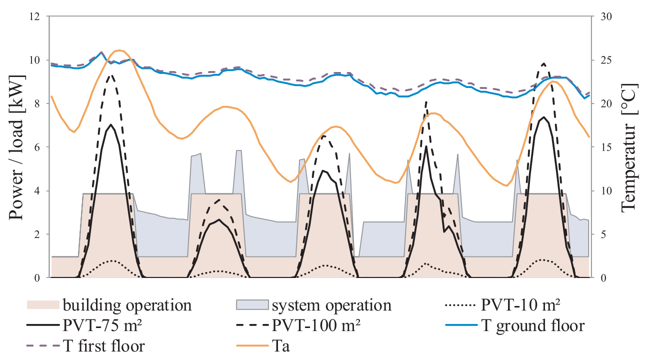

Fig. 5. System behaviour for 5 hot summer days in Moscow passive building, storage tank V = 1 m^3 and three representative PVT collector areas.

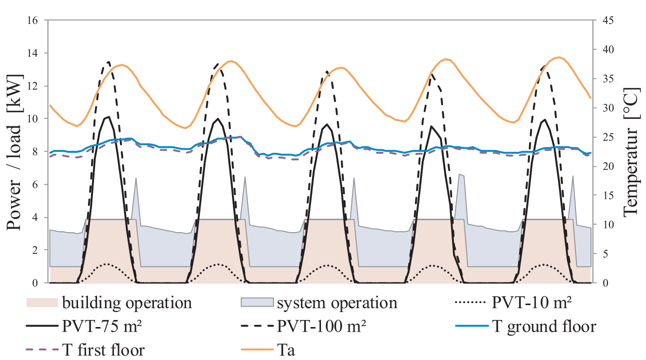

Fig. 6. System behaviour for 5 hot summer days in Dubai passive building, storage tank V = 1 m^3 and three representative PVT collector areas.

26 °C, even if the outdoor temperature is significantly higher (in the Dubai case).

3.2. System costs, cost savings and payback times

The best system configurations with the lowest system investment costs of 19 682 € could be found in Moscow for a small PVT system for the building in the passive house standard, and the highest with 66 132 € in Stuttgart for the building stock (building standard 2). The system costs for the building stock in Moscow are comparable to Dubai stock, however the investment costs of the passive building are slightly lower. The costs for energy production are the highest in Germany, with a range of 0.066–0.09 €/kWh_{cold} for cooling and 0.114–0.189 €/kWh_{heat} for heating. The lowest total energy costs with 0.050 €/kWh could be found for Dubai.

In all cases the energy production costs are lower for the building stock. In countries without compensation models, specific energy production costs strongly depend on the electricity price. For countries like Germany where feed in tariffs exist, cost savings of up to 6483 € per year compared to the reference system can be achieved. In some cases (e.g. high collector field area in Dubai and Moscow), the renewable energy system is even more expensive compared to the reference system, due to the high investment costs and a high auxiliary energy consumption. The payback times are in a range of 4.6 for Stuttgart and 9.2 years for the location of Moscow. Most of the system combinations can be considered as economically feasible. High investment costs of the PVT system could be compensated by cost savings through self-consumption due to the high electricity prices in Germany. In Dubai, on the other hand, payback times in the range of 5 years only occur for small system dimensions. The following Table 7 presents a summary of the best system configurations for all cases and all locations. The seasonal performance factor (SPF) for heating is between 3.6 and 4.8 and the SPF for cooling is between 5.7 and 6.5, compared to other conventional systems, which can be considered as very good.

3.3. System size for zero energy buildings

A zero energy building should consume less energy as it consumes during a specified period of time, typically a year. Table 8 shows the electricity balance of the passive house standard building over one year. For locations like Moscow a minimum collector field area of 75 m^2 is required to meet the requirements of a zero energy building. Locations with a higher solar radiation meet the requirements with a collector field area of 50 m^2. However, the framework conditions in Dubai and Moscow are not given from an economic point of view, which is particularly noticeable when looking at the payback period. The payback period in Moscow increases from 7 years to 15.7 years and in Dubai from 5.3 to 9.9 years.

4. Conclusion

The aim of this study was to investigate the use of hybrid collectors (PVT) for trigeneration of electricity, heat and cold. To analyse the potential of PVT systems to achieve net zero energy, passive building standards were compared to more conventional construction standards. The proposed system design (PVT system with rev. HP) shows a high energy potential for the integration of renewable energies, higher self-consumption of local energy, and lower energy production costs compared to conventional systems (reference system with air-to-water heat pumps). The following recommendations on system design can be drawn from the research:

- PVT collectors can be integrated into a building's energy system as a heat source and heat sink for a reversible HP. Such an energy system has an economic advantage only in applications where heat, cold and electricity is needed. Especially non-residential buildings such as office buildings offer optimal boundary conditions for PVT systems.
- The proposed PVT system is appropriate for different climate conditions and building standards.
- For cities like Moscow or Dubai, with no existing feed in tariffs for renewable energies, only small collector areas of only 10 m^2 are economically feasible
- Large PVT systems in Russia and UAE (or in countries with similar renewable energy pricing policies, in general) are not economical.
- Even for locations with high potential for PV-electricity production, the large area design for the proposed PVT system is only feasible with a feed-in tariff system or within the frame of free energy trading on the neighborhood level (like in some African countries).
- For Stuttgart, on the other hand, areas of up to 100 m^2 can be installed. The large PVT area does not only have a positive effect on CO_2 savings, but also results in high financial savings.
- Hence, markets with feed in tariff structures like in Germany, offer

Table 7
Summary of the best system configurations for all cases and all locations.

	Unit	Moscow		Stuttgart		Dubai	
		passive	stock	passive	stock	passive	stock
Collector field area	m^2	10	10	100	100	10	10
Storage volume	m^3	2	1	1	2	1	2
Investment costs (K_I)	€	19,682	37,212	55,672	66,132	24,452	37,894
Capital costs	€/a	1513	2861	4280	5084	1880	2913
Rel. capital costs	%	62	49	143	85	72	69
Operational costs ($C_{a,c}$)	€/a	204	385	576	684	253	392
Rel. operational costs	%	8	7	19	11	10	9
Consumption costs	€/a	890	2743	−1754	4105	477	1061
Rel. consumption costs	%	30	44	−62	4	18	21
Annual cost savings (ΔC_a)	€/a	371	293	4992	6483	801	1146
Total energy production costs	€/kWh	0.089	0.067	0.146	0.112	0.050	0.050
Energy production costs for heat	€/kWh	0.101	0.067	0.189	0.114	–	–
Energy production costs for cold	€/kWh	0.058	0.046	0.090	0.066	0.050	0.050
Seasonal performance factor (SPF) heating season	–	4.0	4.3	3.6	4.8	–	–
SPF cooling season	–	6.5	5.7	6.3	6.5	5.9	5.9
SPF total	–	4.4	4.3	4.6	4.8	5.8	5.9
Total PE savings (PE_{save})	kWh/a	15,142	18,202	46,145	55,165	39,601	56,607
Rel. PE savings	%	47	25	108	84	66	62
Costs for primary energy (PE) savings ($C_{PE,save}$)	€/kWh	0.025	0.016	0.108	0.118	0.020	0.020
Payback time ($\tau_{payback}$)	a	7.3	9.2	5.3	4.6	5.3	5.0
CO_2-savings	t/a	10	12	30	36	26	36
Self consumption (electricity)	kWh/a	1044	1044	9603	9920	2202	2202
Grid feed in	kWh/a	–	–	4 584	4 273	–	–
Grid consumption	kWh/a	27,152	42,713	15,717	22,166	8650	33032

Table 8
Electricity balance and payback time for the passive house for all three locations with different collector field area.

	Moscow		Stuttgart		Dubai	
Collector field area [m^2]	Electricity balance [kWh/a]	$\tau_{payback}$ [a]	Electricity balance[kWh/a]	$\tau_{payback}$[a]	Electricity balance[kWh/a]	$\tau_{payback}$[a]
10	−6316	7.3	−3318	2.1	−6676	5.3
25	−4228	10.3	−954	3.1	−2273	7.3
50	−1097	12.8	2593	3.8	4332	9.9
75	2034	15.7	6140	4.6	10,936	13.6
100	5164	18.8	9686	5.3	17,541	17.7

good conditions for first prototype applications.

- Zero energy or even plus energy office buildings are feasible under all climatic conditions, if longer payback times are acceptable.

The system has not yet been validated under real operation conditions. So far, only the theoretical potential of such a system has been demonstrated. An ongoing research project (PVT-RESyst funded by BMBF) is considering practical installations and real demonstration of PVT-Systems for trigeneration in hot climates, including an economic assessment.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

AHK, 2013. AHK-Geschäftsreise. Russland vom 02.-. bis 07. Dezember 2013 in Moskau. http://www.eclareon.com/sites/default/files/ee_factsheet_2013.pdf.
Al-Nimr, M.A., Kodah, Z., Nassar, B., 1998. A theoretical and experimental investigation of a radiative cooling system. Sol. Energy 63 (6), 367–373.
Balaras, C.A., Grossman, G., Henning, H.-M., Infante Ferreira, C.A., Podesser, E., Wang, L., Wiemken, E., 2007. Solar air conditioning in Europe—an overview. Renew. Sustain. Energy Rev. 11 (2), 299–314.
Bartoli, B., Catalanotti, S., Coluzzi, B., Cuomo, V., Silvestrini, V., Troise, G., 1977. Nocturnal and diurnal performances of selective radiators. Appl. Energy 3 (4), 267–286.
Bergene, T., Løvvik, O.M., 1995. Model calculations on a flat-plate solar heat collector with integrated solar cells. Sol. Energy 55 (6), 453–462.
Bilgili, M., 2011. Hourly simulation and performance of solar electric-vapor compression refrigeration system. Sol. Energy 85 (11), 2720–2731.
Brown, F.E., Rickaby, P.A., Bruhns, H.R., Steadman, P., 2000. Surveys of nondomestic buildings in four English towns. Environ. Plann. B: Plann. Des. 27 (1), 11–24.
Buonomano, A., Calise, F., Palombo, A., 2013. Solar heating and cooling systems by CPVT and ET solar collectors: A novel transient simulation model. Appl. Energy 103, 588–606.
Buonomano, A., Calise, F., Vicidomini, M., 2016. Design, simulation and experimental investigation of a solar system based on PV panels and PVT collectors. Energies 9 (7), 497.
Cardinale, N., Rospi, G., Ruggiero, F., 2010. Economic-environmental performance indexes for solarpowered absorption cooling system in Mediterranean area. Int. J. Energy Environ. 1 (4), 573–588.
Charalambous, P.G., Maidment, G.G., Kalogirou, S.A., Yiakoumetti, K., 2007. Photovoltaic thermal (PV/T) collectors: A review. Appl. Therm. Eng. 27 (2–3), 275–286.
Chow, T.T., 2010. A review on photovoltaic/thermal hybrid solar technology. Appl. Energy 87 (2), 365–379.
Cox, C.H., Raghuraman, P., 1985. Design considerations for flat-plate-photovoltaic/thermal collectors. Sol. Energy 35 (3), 227–241.

Cremers, J., Eicker, U., Palla, N., Jobard, X., Klotz, F., Mitina, I., 2016. Multivalente photovoltaisch-thermische Kollektoren zur Kälte-, Wärme- und Stromerzeugung und Szenarien für die Gebäudeintegration (PVTintegral): Projektbericht: Laufzeit: 01.09. 2012 bis 31.10.2015, Stuttgart.
Desideri, U., Proietti, S., Sdringola, P., 2009. Solar-powered cooling systems: Technical and economic analysis on industrial refrigeration and air-conditioning applications. Appl. Energy 86 (9), 1376–1386.
Destatis, 2018. Daten zur Energiepreisentwicklung. https://www.destatis.de/DE/Publikationen/Thematisch/Preise/Energiepreise/EnergiepreisentwicklungPDF_5619001.pdf?_blob=publicationFile.
DEWA, 2018. Electricity Tariff - Residentia/Commerial. Dubai Electricity & Water Authority. https://www.dewa.gov.ae/en/customer/services/consumption-services/tariff.
Dimoudi, A., Androutsopoulos, A., 2006. The cooling performance of a radiator based roof component. Sol. Energy 80 (8), 1039–1047.
DIN, 2013. DIN 4108-2:2013-02. Thermal protection and energy economy in buildings - Part 2: Minimum requirements to thermal insulation. Deutsche Industrie Norm.
DIN, 2018. DIN V 18599-10:2018-09. Energy efficiency of buildings - Calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting - Part 10: Boundary conditions of use, climatic data. Deutsche Industrie Norm.
Dupeyrat, P., Ménézo, C., Rommel, M., Henning, H.-M., 2011. Efficient single glazed flat plate photovoltaic–thermal hybrid collector for domestic hot water system. Sol. Energy 85 (7), 1457–1468.
Eicker, U., Dalibard, A., 2011. Photovoltaic–thermal collectors for night radiative cooling of buildings. Sol. Energy 85 (7), 1322–1335.
Eicker, U., Pietruschka, D., 2009. Design and performance of solar powered absorption cooling systems in office buildings. Energy Build. 41 (1), 81–91.
Eicker, U., Pietruschka, D., Schmitt, A., Haag, M., 2015. Comparison of photovoltaic and solar thermal cooling systems for office buildings in different climates. Sol. Energy 118.
Erell, E., Etzion, Y., 2000. Radiative cooling of buildings with flat-plate solar collectors. Build. Environ. 35 (4), 297–305.
Fong, K.F., Chow, T.T., Lee, C.K., Lin, Z., Chan, L.S., 2010. Comparative study of different solar cooling systems for buildings in subtropical city. Sol. Energy 84 (2), 227–244.
Garg, H.P., Agarwal, R.K., Bhargava, A.K., 1990. Experimental and theoretical studies on a photovoltaic/thermal hybrid solar collector water heater. In: Clean and safe energy forever, 1st ed. Pergamon Pr, Oxford, pp. 701–705.
GEMIS. Internationale Institut für Nachhaltigkeitsanalysen und -strategien (IINAS). Globales Emissions-Modell integrierter Systeme (GEMIS). http://iinas.org/gemis-de.html. Accessed 11 March 2019.
Good, C., Andresen, I., Hestnes, A.G., 2015. Solar energy for net zero energy buildings – A comparison between solar thermal, PV and photovoltaic–thermal (PV/T) systems. Sol. Energy 122, 986–996.
Guo, J., Lin, S., Bilbao, J.I., White, S.D., Sproul, A.B., 2017. A review of photovoltaic thermal (PV/T) heat utilisation with low temperature desiccant cooling and dehumidification. Renew. Sustain. Energy Rev. 67, 1–14.
Hansen, J., Sorensen, H., 2006. IEA SHC Task 35. PV/Thermal Solar Systems. http://task35.iea-shc.org/. Accessed 30 October 2018.
Hartmann, N., Glueck, C., Schmidt, F.P., 2011. Solar cooling for small office buildings: Comparison of solar thermal and photovoltaic options for two different European climates. Renew. Energy 36 (5), 1329–1338.
Hayakashi, B., Mizusaki, K., Satoh, T., Hatanaka, T., 1990. Research and development of photovoltaic/thermal hybrid solar power generation system. In: Clean and safe energy forever, 1st ed. Pergamon Pr, Oxford, pp. 302–306.
Hendrie, S.D., 1979. Evaluation of combined photovoltaic/thermal collectors. Sun II; Proceedings of the Silver Jubilee Congress, Atlanta, Ga., May 28-June 1, 1979. Volume 3.
Herrando, María, Markides, Christos N., Hellgardt, Klaus, 2014. A UK-based assessment of hybrid PV and solar-thermal systems for domestic heating and power: System performance. Appl. Energy 122, 288–309. https://doi.org/10.1016/j.apenergy.2014.01.061.
Henning, H.-M. (Ed.), 2004. Solar-assisted air-conditioning in buildings. A handbook for planners; [Task 25 of the International Energy Agency (IEA) Solar Heating and Cooling Programme. Springer, Wien, 14 pp.
Henning, H.-M., Döll, J., 2012. Solar systems for heating and cooling of buildings. Energy Procedia 30, 633–653.
Huang, B.J., Lin, T.H., Hung, W.C., Sun, F.S., 2001. Performance evaluation of solar photovoltaic/thermal systems. Sol. Energy 70 (5), 443–448.
IEA SHC, 2007. Task 32 – Advanced storage concepts for solar and low energy buildings. The Reference Heating System, the Template Solar System of Task 32. Solar Heating & Cooling Programme.
IEA SHC, 2009. Task 38 Solar Air-Conditioning and Refrigeration. Benchmarks for comparison of system simulation tools - Absorption chiller simulation comparison. A technical report of subtask C. Deliverable C2-B. Solar Heating & Cooling Programme.
International Energy Agency, 2018. The Future of Cooling. Opportunities for Energy Efficient Air Conditioning. International Energy Agency.
Isaac, M., van Vuuren, D.P., 2009. Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. Energy Policy 37 (2), 507–521.
Iziomon, M.G., Mayer, H., Matzarakis, A., 2003. Downward atmospheric longwave irradiance under clear and cloudy skies: Measurement and parameterization. J. Atmos. Sol. Terr. Phys. 65 (10), 1107–1116.
Jakob, U., Eicker, U., Schneider, D., Taki, A.H., Cook, M.J., 2008. Simulation and experimental investigation into diffusion absorption cooling machines for air-conditioning applications. Appl. Therm. Eng. 28 (10), 1138–1150.
Joemann, M., Oezcan, T., Kauffeld, M., Pollerberg, C., 2016. Process steam and chilled water production with CPC-collectors, Steam Jet Ejector Chiller and Latent Heat Storages. Energy Procedia 91, 767–776.
Johnson, D.H., 1983. Quantum and Thermal Conversion of Solar Energy to Useful Work. Solar Energy Research Inst, Golden, CO (United States).
Ju, X., Xu, C., Hu, Y., Han, X., Wei, G., Du, X., 2017. A review on the development of photovoltaic/concentrated solar power (PV-CSP) hybrid systems. Sol. Energy Mater. Sol. Cells 161, 305–327.
Kalogirou, S.A., Tripanagnostopoulos, Y., 2006. Hybrid PV/T solar systems for domestic hot water and electricity production. Energy Convers. Manage. 47 (18–19), 3368–3382.
Kumar, A., Baredar, P., Qureshi, U., 2015. Historical and recent development of photovoltaic thermal (PVT) technologies. Renew. Sustain. Energy Rev. 42, 1428–1436.
Kumar, R., Rosen, M.A., 2011. A critical review of photovoltaic–thermal solar collectors for air heating. Appl. Energy 88 (11), 3603–3614.
Lalović, B., Kiss, Z., Weakliem, H., 1986. A hybrid amorphous silicon photovoltaic and thermal solar collector. Solar Cells 19 (2), 131–138.
Lazzarin, R.M., 2014. Solar cooling: PV or thermal? A thermodynamic and economical analysis. Int. J. Refrig. 39, 38–47.
Lu, X., Xu, P., Wang, H., Yang, T., Hou, J., 2016. Cooling potential and applications prospects of passive radiative cooling in buildings: The current state-of-the-art. Renew. Sustain. Energy Rev. 65, 1079–1097.
Meteotest, 2014. Meteonorm Datenbank. http://www.meteonorm.com/. Accessed 21 December 2018.
Michael, J.J., Iniyan, S., Goic, R., 2015. Flat plate solar photovoltaic–thermal (PV/T) systems: A reference guide. Renew. Sustain. Energy Rev. 51, 62–88.
Otanicar, T., Taylor, R.A., Phelan, P.E., 2012. Prospects for solar cooling – An economic and environmental assessment. Sol. Energy 86 (5), 1287–1299.
Palla, N., Braun, R., Jobard, X., Mitina, I., Cremers, J., Eicker, U., 2014. Development of Multivalent PV-Thermal Collectors for Cooling, Heating and Generation of Electricity. In: 30th International PLEA Conference: SUSTAINABLE HABITAT FOR DEVELOPING SOCIETIES – Choosing The Way Forward (Proceedings Vol.2), S., pp. 550–558. Online verfügbar unter. http://www.plea2014.in/presenting-author-list/.
Pollerberg, C., Kauffeld, M., Oezcan, T., Koffler, M., Hanu, L.G., Doetsch, C., 2012. Latent heat and cold storage in a solar-driven steam jet ejector chiller plant. Energy Procedia 30, 957–966.
Riffat, S.B., Cuce, E., 2011. A review on hybrid photovoltaic/thermal collectors and systems. Int. J. Low-Carbon Technol. 6 (3), 212–241.
Saghafifar, M., Gadalla, M., 2016. Performance assessment of integrated PV/T and solid desiccant air-conditioning systems for cooling buildings using Maisotsenko cooling cycle. Sol. Energy 127, 79–95.
Sandnes, B., Rekstad, J., 2002. A photovoltaic/thermal (PV/T) collector with a polymer absorber plate. Experimental study and analytical model. Sol. Energy 72 (1), 63–73.
SIA, 2011. SIA 380/4. Elektrische Energie, SIA 380/4, Teil Beleuchtung. Swiss Society of Engineers and Architects.
Steadman, P., Bruhns, H.R., Holtier, S., Gakovic, B., Rickaby, P.A., Brown, F.E., 2000. A classification of built forms. Environ. Plann. B: Plann. Des. 27 (1), 73–91.
Tjarko, T., 2013. Techno-ökonomischer Vergleich von Solarthermieanlagen mit Photovoltaik-Wärmepumpen-Systemen mittels dynamischer Simulation, Berlin.
Tripanagnostopoulos, Y., 2007. Aspects and improvements of hybrid photovoltaic/thermal solar energy systems. Sol. Energy 81 (9), 1117–1131.
Tripanagnostopoulos, Y., Nousia, T., Souliotis, M., Yianoulis, P., 2002. Hybrid photovoltaic/thermal solar systems. Sol. Energy 72 (3), 217–234.
TRNSYS 17, 2018. TRNSYS 17. TRNSYS User Manual - Multizone Building modeling with Type 56 and TRNBuild.
Umweltbundesamt, 25/2014. Nachhaltige Kälteversorgung in Deutschland an den Beispielen Gebäudeklimatisierung und Industrie.
VDI, 2013. VDI 2067 - 10:2013-09. Economic efficiency of building installations - Energy demand for heating, cooling, humidification and dehuminification.
Wu, J., Zhang, X., Shen, J., Wu, Y., Connelly, K., Yang, T., Tang, L., Xiao, M., Wei, Y., Jiang, K., Chen, C., Xu, P., Wang, H., 2017. A review of thermal absorbers and their integration methods for the combined solar photovoltaic/thermal (PV/T) modules. Renew. Sustain. Energy Rev. 75, 839–854.
Yousfi, M.L., Saighi, M., Dalibard, A., Schneider, D., Eicker, U., 2017. Performance of a 5 kW hot water driven diffusion absorption chiller. Appl. Therm. Eng. 127, 789–799.
Zondag, H.A., 2008. Flat-plate PV-Thermal collectors and systems: A review. Renew. Sustain. Energy Rev. 12 (4), 891–959.
Zondag, H.A., de Vries, D.W., van Helden, W.G.J., van Zolingen, R.J.C., van Steenhoven, A.A., 2003. The yield of different combined PV-thermal collector designs. Sol. Energy 74 (3), 253–269.