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Simulation Study of Solar Thermal and Photovoltaic Collector Options for Solar-Assisted Heating of a Residential Building in Germany

Amar Abdul-Zahra[1,2], Tillman Faßnacht[2], Christian Glück[2] and Andreas Wagner[2]
[1]University of Technology-Iraq, [2]Karlsruhe Institute of Technology

***Abstract* – Flat plate solar thermal collectors and photovoltaic solar collectors in combination with an electrical resistance heater have been compared as an additional solar heat source of a gas burner-based heating system for a residential building in Germany. The dependency on solar collector field area and retrofitting level of the building has been analyzed in parametric studies. On the economic side, the results are in favor of the photovoltaic-based collector option, which is largely due to significant reductions of the grid-supplied electric power and the electrical household demand. On the energy efficiency side, the thermal collector-based variant requires smaller collector field areas and causes lower fossil demands for heating. The analyses have been done taking into account different primary energy factors and different cost assumptions.**

***Keywords* – Solar thermal collector, photovoltaic system, gas condensing boiler, electrical resistance heater.**

I. Introduction

Many installations of solar-assisted heating systems in Germany are based on a combination of solar thermal collectors, hot water storage and a heat generator, which is usually either a gas, oil, or wood boiler, or a heat pump. In these installations, the solar energy is delivered directly to the hot water storage, whereby the demand for heating and hot water can be partly covered by heat produced by the solar collectors (see Fig. 1 for a typical set up of such a system). Due to the worldwide decrease of initial costs of PV systems [1], a new approach to solar-assisted heating could become economical: PV fields for power generation and heating systems with thermal storages that are equipped with electrical resistance heaters. The electrical energy generated by the PV field can then be supplied to cover the electrical household demand at the highest priority, at the second priority to the electric resistance heater[1] and at the lowest priority it can be fed into the electrical grid (see Fig. 2 for a scheme of such a system).

This study makes an attempt to shed some light on the relevant factors house owners have to take into account when deciding on solar-assisted heating systems for their buildings. Two building standards have been studied. The first building standard (building A) represents a retrofitted building and the second building standard (building B) – a stock level building. Further two different household electrical demands have been used in the simulations. The primary energy consumption and the CO_2 emissions of the individual buildings have been evaluated and full cost calculations of the solar-assisted heating systems have been conducted as well.

[1] Note: Here, theoretically a small heat pump could also be used.

II. Simulation Scenario and Control Strategy

Both systems in Fig. 1 and 2 have been modeled in TRNSYS 17 [2]. A building with 180 m² conditioned area has been simulated, where two different building retrofitting standards have been taken into account: building A, with 52 kWh m^{-2} a^{-1} heating demand and building B with 100 kWh m^{-2} a^{-1}. The buildings are equipped with floor heating systems. Climate data for Würzburg, Germany, has been used in the simulations. The domestic hot water demand of all buildings was set to (11.3 kWh m^{-2} a^{-1}), based on a tapping profile developed in the IEA Task 44 [14]. Two different time series based on the German guideline VDI 4655 [3] for the electrical household demand have been used in the simulations. Table 1 presents the evaluated combinations.

TABLE 1
HEAT DEMAND AND ELECTRICAL HOUSEHOLD DEMAND OF THE BUILDINGS.

Building	Heat Demand [kWh/(m²a)]	El. Household demand [kWh/a]
Building A-1	52	4141[2]
Building A-2	52	2070
Building B	100	4141

The set point of the flow temperature to the floor heating is calculated according to a heating curve $Th_d = f(T_{amb})$, where the dimensioning temperatures are 35 °C flow and 30 °C return temperature. The solar supported heat source in the building was chosen to be a gas condensing boiler. Different solar thermal collector field areas (2.5, 5, 15, 23.5, 39 m²) along with the adapted hot water storage tank volumes for each solar thermal area and PV fields of different peak powers (2.2, 2.6, 3.3, 5.5 kWp) were simulated. Type 204 [4] has been used to simulate the gas boiler in TRNSYS. The nominal power of the simulated gas boiler is 14.5 kW. For the solar

[2] According to [13], the average electrical demand of a one-person household in Germany is 1,700 kWh/a, of a two-person household – 3,000 kWh/a and of a four-person household – 4,200 kWh/a (without electrical demand for heating and domestic hot water).

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thermal collector field, a single speed pump with hysteresis control is used.

In order to increase the local energy consumption, the electrical energy generated by PV panels is supplied at the first priority to the building (in order to cover household electrical demand), at the second priority to the electrical resistance heater (ERH), and at the third priority to the electrical grid. The electrical resistance heater is used as long as the storage temperatures are below 85 °C. Feed in compensation (monetary and primary energy compensation) for electricity fed into the grid is neglected. The monetary feed in compensation is – on a long-term scale – an unpredictable figure, which depends on governmental guidelines and is subject to change. Fed in electricity to the grid replaces conventional electricity generation and results in lower primary energy consumption and CO_2 emissions for the overall electricity generation. This is taken into account by the primary energy factor for electricity. For that reason no additional primary energy compensation for fed in electricity has been taken into account, whereas the results in this paper are presented in dependence of different primary energy factors. The primary energy calculations are based on every minute balances.

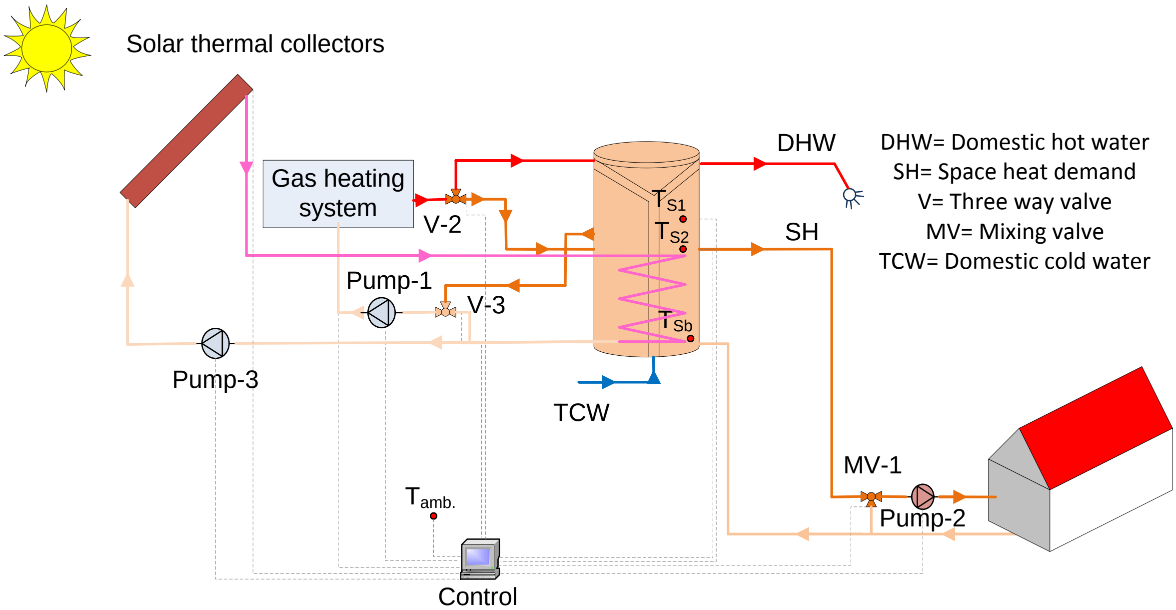


Fig. 1. Scheme of the evaluated gas boiler heating system combined with a solar thermal system.

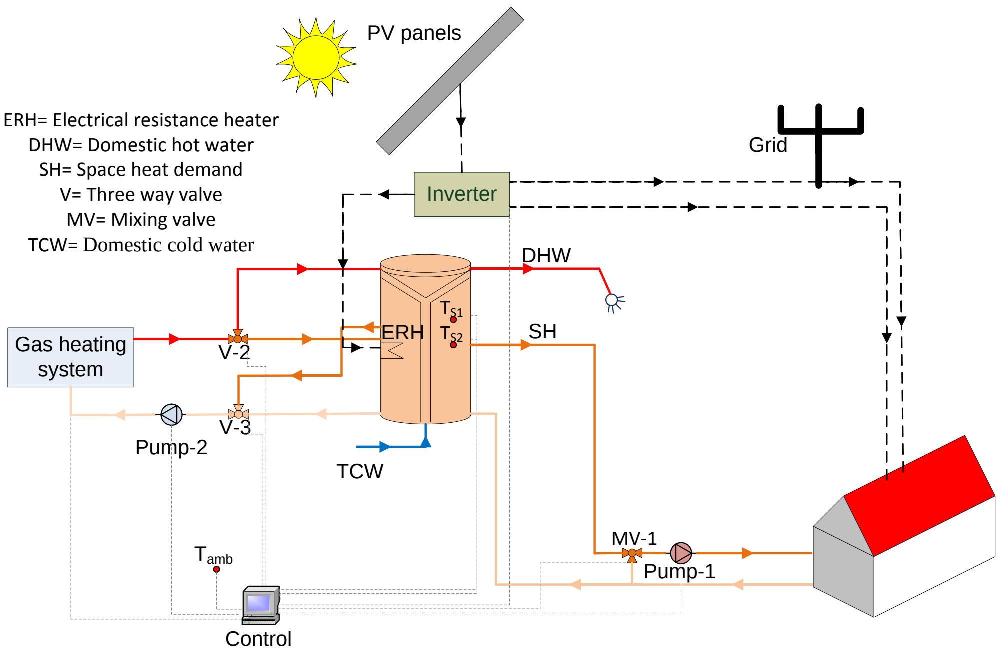


Fig. 2. Scheme of the evaluated gas boiler heating system combined with a PV system.

III. PRIMARY ENERGY CONSUMPTION AND CO_2 EMISSIONS

Primary energy consumption and CO_2 emissions of the buildings have been calculated. The balance boundary is just the building itself, i.e. the energy demand of the heating system and the household is taken into account. Table 2 shows the used primary energy factors according to German EnEV 2009 [5] and the used CO_2 emission factors according to *Großklos*, 2014 [15] (the CO_2 factors are thereby based on GEMIS version 4.5 [6]).

TABLE 2
PRIMARY ENERGY AND CO_2 EMISSION FACTORS.

Energy carrier	Primary energy factor	CO_2-production [kg/kWh]
Natural gas	1.1	0.244
Electrical energy	2.6[3]	0.633

The primary energy consumption for the building is calculated via formula (1). The primary energy savings are calculated according to formula (2) [7]:

$$Q_{system} = \sum E_{need} \cdot f_p \tag{1}$$

$$f_{sav} = 1 - \frac{Q_{system}}{Q_{\mathrm{Re}\,f}}. \tag{2}$$

Where:

E_{need} : End energy consumption of electricity and gas.

f_p : Primary energy factor.

f_{sav} : Primary energy saving.

Q_{system}: Primary energy demand of the individual building with a solar energy system.

$Q_{\mathrm{Re}\,f}$: Primary energy demand of the reference system without any solar energy system.

The reference system refers to the building without any kind of solar system, just with a gas condensing boiler heating system.

IV. FULL COST CALCULATION

Calculations presented below are based on the annuity method in VDI 2067 [8]. The components that are present in all investigated systems, such as the gas boiler, the heat distribution, the gas connection and chimney, etc., were not implemented in the full cost calculations to limit the focus of this study to the cost of the (additional) solar system. Different energy cost assumptions have been made in a sensitivity analysis on cost assumptions. Table 3 summarizes the cost assumptions of the system components and energy prices per kWh based on (example) list prices in the German market [1, 9-12].

[3] This is just the basis case, later in the paper the results are displayed for different primary energy factors.

TABLE 3
COST ASSUMPTIONS

Product	Note	Price [€]
Hot water tank with ERH	0.56, 1, 2 m³ without solar heat exchanger	1,500, 1,800, 3,000
Hot water tank	0.56, 1, 2 m³ with solar heat exchanger	1,800, 2,060, 3,250
Hot water tank with solar heat exchanger and ERH	0.56, 1 m³	2,100, 2,300
Solar thermal system, complete (including the installation cost)	2.5, 5, 15, 23.5, 39 m² flat plate solar collector	2,500, 4,000, 8,600, 12,500, 18,000
PV system (including the installation cost)	entire system per kWp	1,700
Energy Source		
Electricity	€cent/kWh	0.26
Gas	€cent/kWh	0.075
Electricity feed-in	€cent/kWh	0
Energy price increase per year		3.6 %
Inflation		2 %
Interest rate		3 %
Lifetime	year	20
VAT		19 %

V. RESULTS

In *subchapter A*, the effect of the hot water storage size on the PV and solar thermal systems is evaluated. Based on the results, the storage volumes are fixed in the rest of the paper. In *subchapter B*, the primary energy consumptions of the different buildings and heating systems are calculated and depicted in dependence of different primary energy factors. In *subchapter C*, primary energy savings of different buildings are compared to those of a building without solar support. In *subchapter D*, the CO_2 emission of the investigated building supply systems with different kinds of solar support systems are evaluated. In *subchapter E*, the results of the full cost calculations are summarized.

A. Effect of the hot water storage volume on the primary energy consumption and the operation costs:

Fig. 3 shows the primary energy consumption (PEC) and operation costs (OC) of Building A-1 with a 3.3 and a 5.5 kWp PV system.

It can be seen that the variation of the hot water storage volumes (within the range given by design limitations of the storage) resulted in relatively low changes in the primary energy consumption and operation costs. A reason for that could be the sufficient storage capacity at smaller capacities due to the limited peak power of the PV field, especially during the cold season.

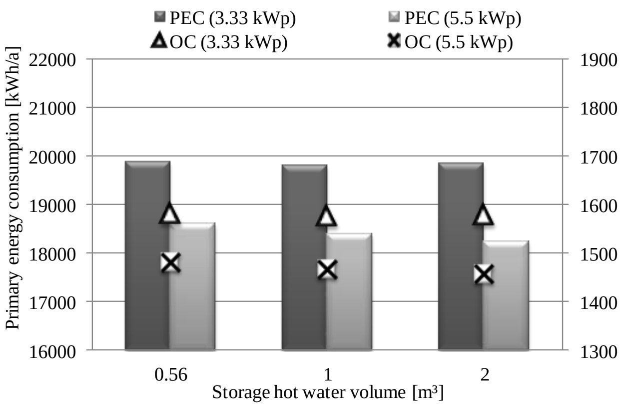


Fig. 3. Primary energy consumption (PEC) and operation cost (OC) with different hot water storage volumes (3.33 kWp = 23.5 m², 5.5 kWp = 39 m² panel area).

Furthermore, the efficiency of the electrical resistance heater does not depend on the storage temperature, which means that the PV supported system does not profit strongly from an increased storage volume. Due to the limited influence of the hot water storage size, and due to relatively high impact on the investment costs, the storage tank size for the proposed PV systems in this paper is limited to 0.56 m³.

Fig. 4 shows the effect of the hot water storage on the primary energy consumption and operation costs for two different solar thermal field areas. Here a slightly larger influence of the hot water storage volume than in the PV case can be observed. This is due to two reasons: firstly, the higher peak power of the collector field areas of the solar thermal[4] systems compared to the PV systems (same collector area), and secondly, the dependence of the solar thermal efficiency of the solar collectors on the hot water storage / supply temperatures.

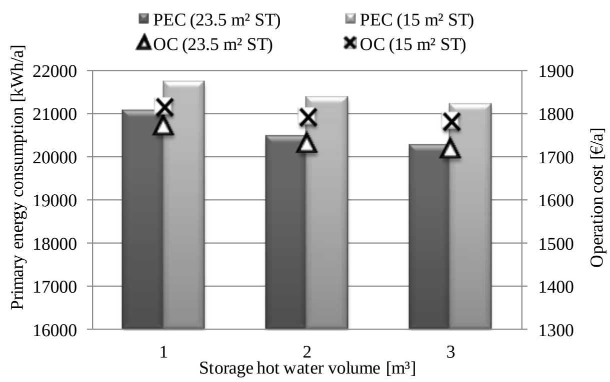


Fig. 4. Effect of the hot water storage volumes on the primary energy consumption (PEC) and operation costs (OC).

Based on the results, the hot water storage volumes in Table 4 have been used in this paper.

[4] The maximum energy conversion rate of the simulated flat plate solar thermal collectors is approximately 0.8, whereas of the simulated PV modules approximately 0.14. Take note: The PV modules produce pure exergy, whereas the solar thermal collectors produce heat with a relative small exergetic proportion.

TABLE 4
HOT WATER STORAGE VOLUMES FIXED IN THIS STUDY.

Type of system	Volume [m³]
PV system (2.2, 3.3, 5.5 kWp)	0.56
Solar thermal collector (5, 15, 23.5, 39 m²)	0.56, 1, 2, 2

B. Overall Primary Energy Consumption:

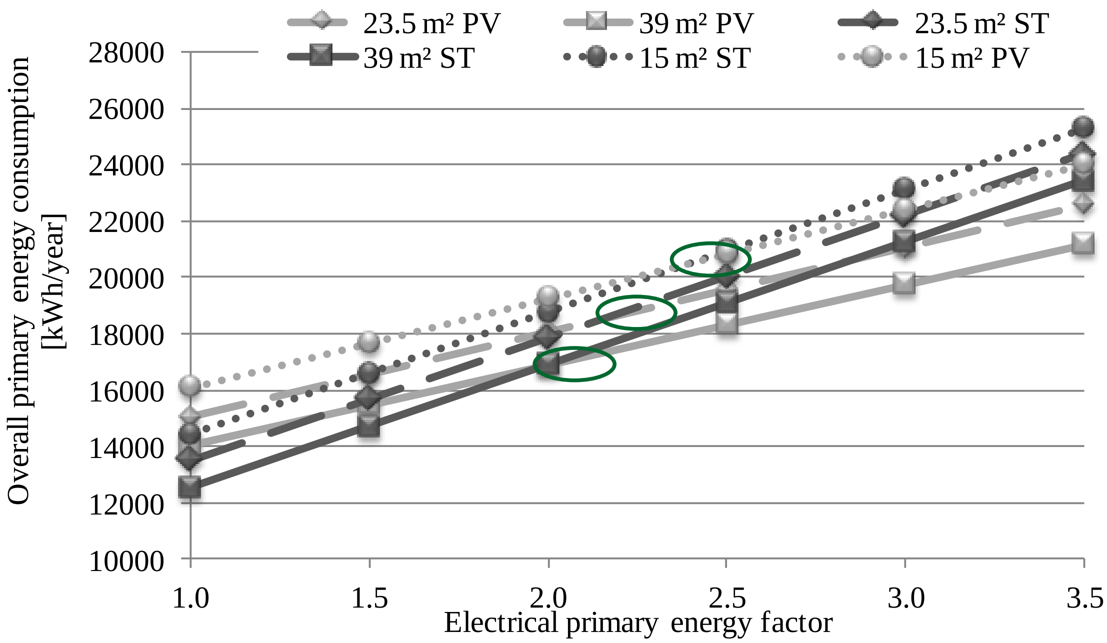
Fig. 5 shows the influence of different electrical primary energy factors on the overall (household + heating demand) primary energy consumption with different solar support systems. Fig. 5a shows the results for Building A-1, Fig. 5b for Building A-2 and Fig. 5c for Building B.

In Fig. 5, the curves corresponding to solar thermal and PV intersect. At the intersection, the other system becomes the one with the lower primary energy consumption. In Fig. 5a this alternation is marked for the cases with the same area of PV and ST. Left of this cross points the buildings with solar thermal supported systems result in lower primary energy consumption, whereas at the right hand side of the intersects the PV supported buildings result in lower primary energy consumption. With rising primary energy factors, the PV-based support results in higher effects due to the less electrical household consumption from the grid due to increased own energy consumption. The share of the electrical household consumption on the total primary energy consumption of the building decreases with the reduced primary energy factors. In Fig. 5b and 5c the cross points (where the same installed area is assumed) are located close to each other.

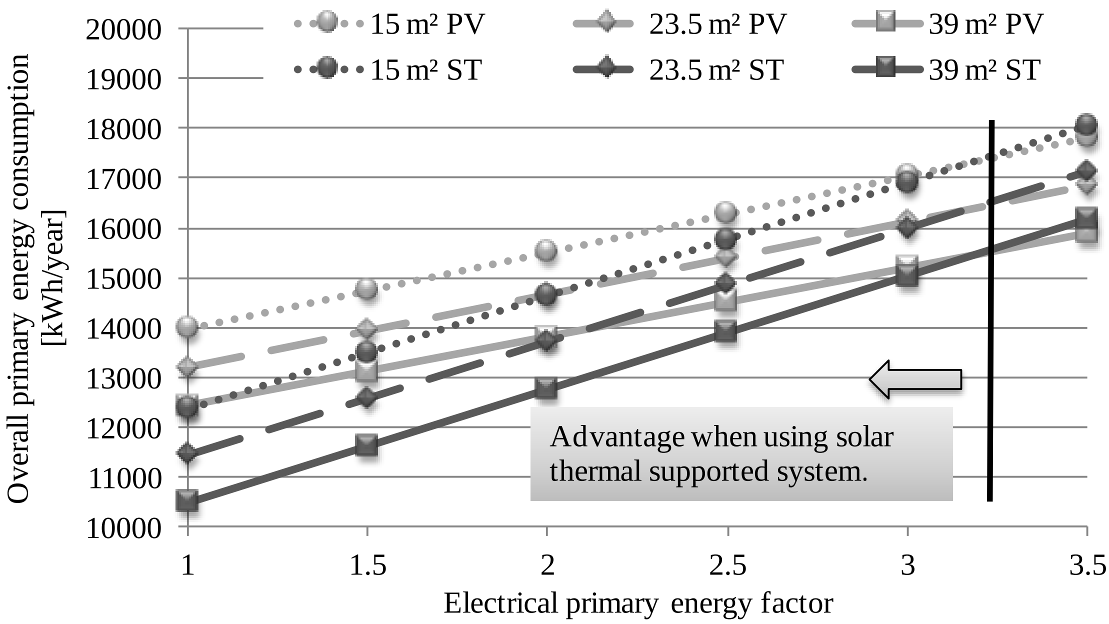
In Fig. 5a and 5c the electrical household demand of the building is the same, but the heating demand of the building is approximately doubled. The cross points shift to the right side, which means that the solar thermal supported supply systems are better than the PV supported systems with increasing heating demand of the building. As one would expect, the point at which using a solar thermal or a PV-based solar support system results in lower primary energy consumption is dependent on the combination of the heating demand and the electrical household demand. In Fig 5a and b the building heat demand is the same, but the electrical household demand differs by a factor of 2. This leads to the shift of the cross points to a primary energy factor of 3.25 in contrast to 2.0-2.5, depending on the peak power, in Fig. 5a.

It can be stated that with an increased heat demand and a constant electrical demand, the solar thermal supported heating system tends to result in lower primary energy consumption of the building. Whereas with falling heat demands, the impact of the electrical household demand on the building's primary energy balance increases, which leads to the PV supported heating system to result in lower primary energy consumption.

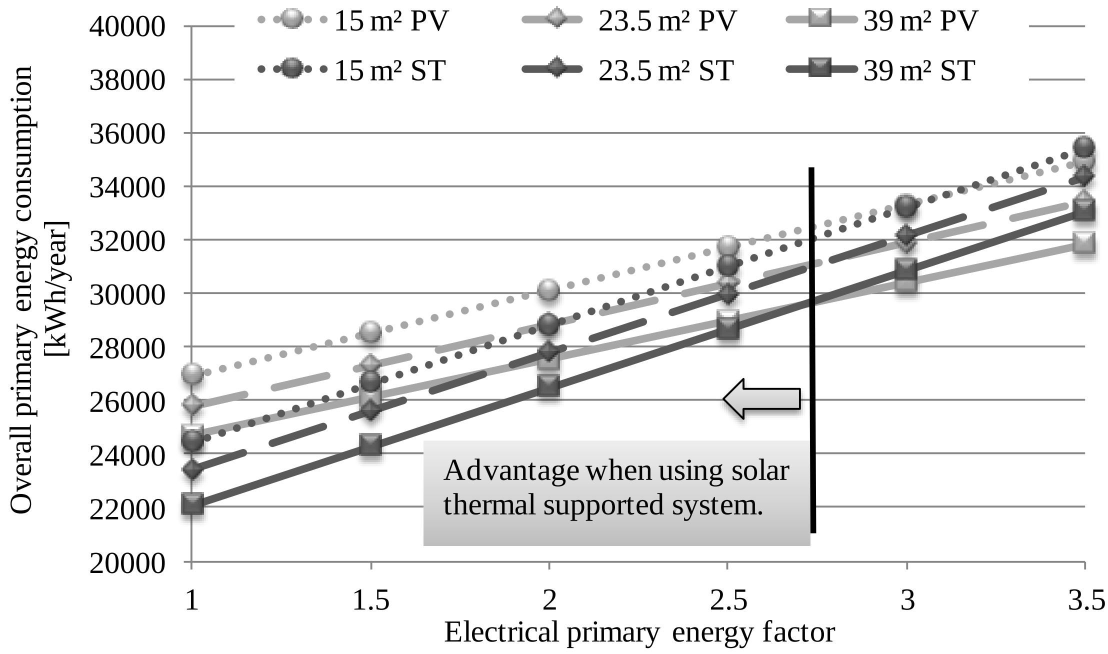
Table 5 summarizes the end energy consumptions of buildings A-1 and B with the same collector area of 23.5 m² in each case. For the solar thermal supported system, this results in a higher reduction of the end energy consumption for heating (gas), whereas the PV supported system also leads to a reduction of the electricity demand from the electrical grid. The overall reduction in end energy is larger for the solar thermal supported system.



(a)



(b)



(c)

Fig. 5. Influence of the primary energy factors on the overall primary energy consumption, black lines represent the results of the solar thermal (ST) supported systems and grey lines are the Photovoltaic (PV) supported systems. Fig. 5a building A-1, Fig. 5b building A-2 and Fig. 5c building B.

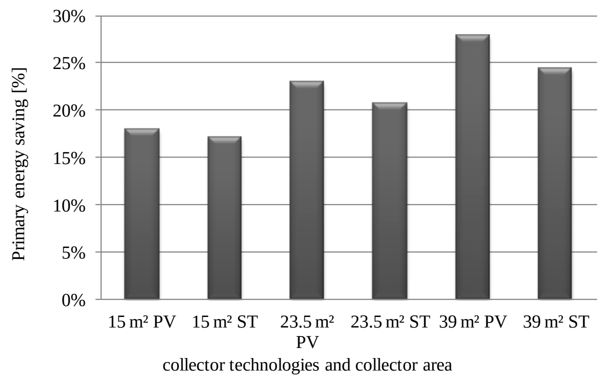
TABLE 5

END ENERGY CONSUMPTIONS OF DIFFERENT DEMAND STRUCTURES OF THE BUILDING (EQUAL COLLECTOR AREA)

Building (23,5 m² collector area)	Electricity demand from grid [kWh][5]		Gas demand [kWh]	
	PV	ST	PV	ST
A-1	3007	4343	10765	8187
A-2	1465	2272	10475	8187
B	3041	4377	20556	16978

C. Primary Energy Savings:

Fig. 6 shows the primary energy savings[6] compared to a building with a gas heating system as in Fig. 1 and 2 and no solar support (building A-1, Fig. 6a; building B, Fig. 6b). With building A-1 (Fig. 6a), the primary energy savings due to the PV supported heating system are larger than those of the solar thermal supported system with the same collector field area. With building B (18,000 kWh heat demand 4141 kWh electricity demand; Fig. 6b), the comparison of solar thermal and PV systems leads to approximately equal PE savings (solar thermal slightly better), due to the higher share of the heat demand in the total primary energy balance.



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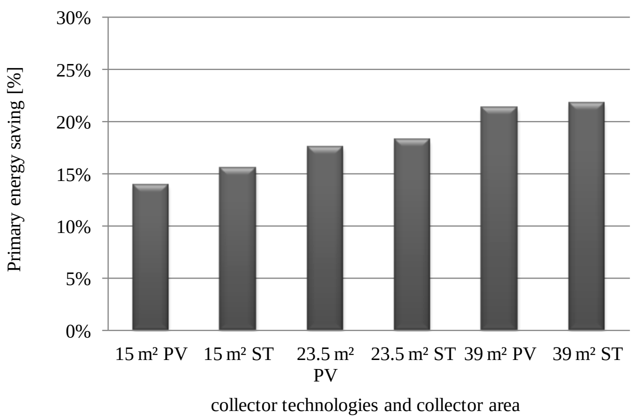


b)

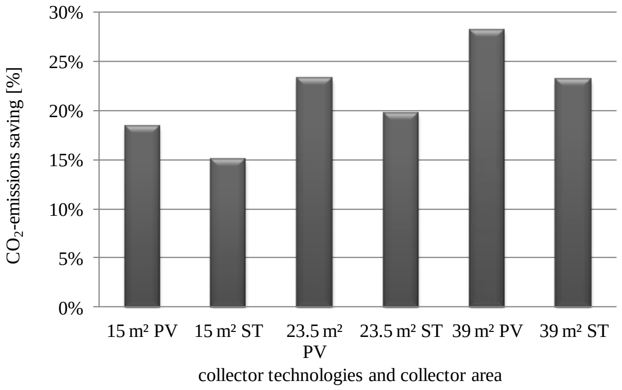
Fig. 6. Total primary energy saving (heating and household electricity) for different systems and areas (a) building A-1; b) building B; primary energy factor for electricity 2.6 and for gas 1.1).

[5] Electrical household demand plus electricity for the heating system.

[6] Note: The primary energy saving refers here to the overall primary energy consumption of the building (consumption for heating and household electricity). The primary energy factor of electricity is set to 2.6 in all this diagrams.

D. CO_2 emissions of the solar supported supply systems:

Fig. 7 shows the CO_2 emission savings compared to a building without solar support (Fig. 7a building A and Fig. 7b building B). For building A (Fig. 7a), an advantage of the PV supported building can be observed. In building B (Fig. 7b), the CO_2 emissions for both system types are very similar.



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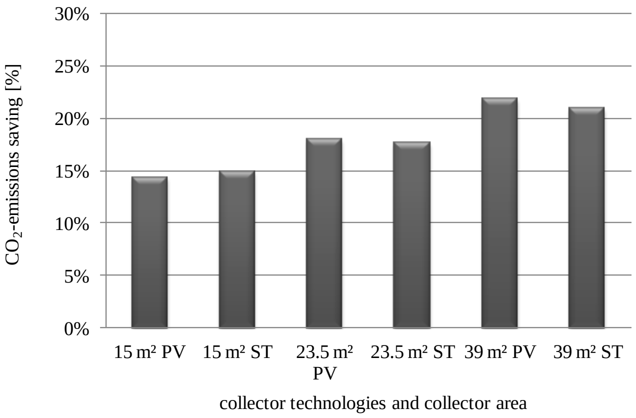


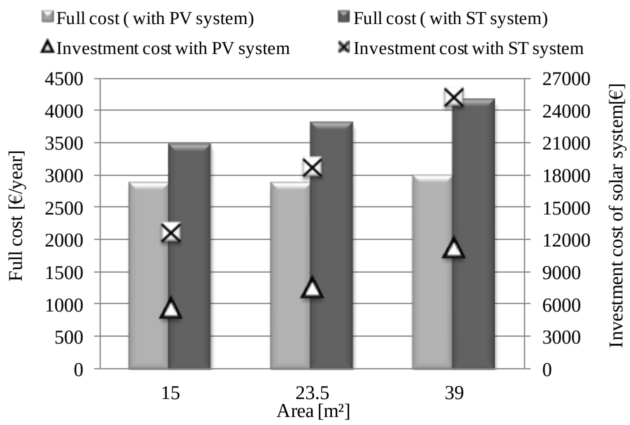
b)

Fig. 7. Total CO_2 savings (heating and household electricity) for different systems and areas (a) building A-1; b) building B; CO_2 emission factor for electricity 0.633 and for gas 0.244).

E. Full Cost Calculation:

Fig. 8 shows the calculated full costs and the investment costs of the different cases (Fig. 8a – building A-1 and Fig. 8b – building B). In these calculations, the total energy price increase per year was assumed to be 3 %.

The results in Fig. 8 show lower full costs for the PV-based systems. The electricity generated by the PV system can reduce the gas demand for heating and reduce the electricity consumption from the grid. Furthermore, the investment costs of the PV supported heating system are to date lower compared to those of the solar thermal system. With increasing heat demand of the building, the difference between the full costs decreases (cf. Fig 8b) due to decreased contribution of the electricity demand to the full costs.



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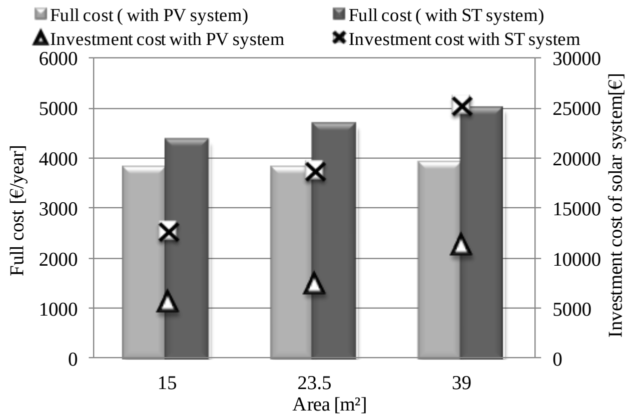
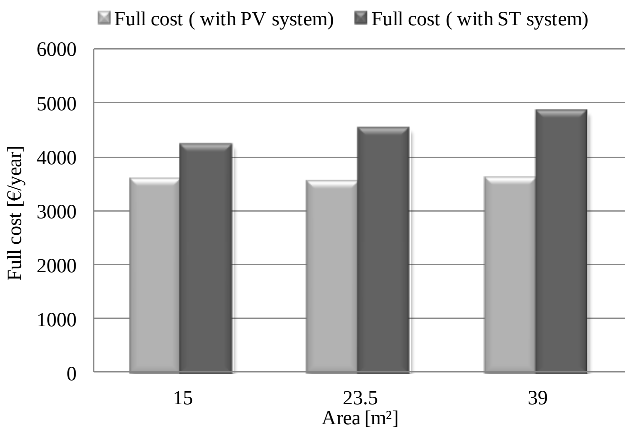


b)

Fig. 8. Full cost and investment cost of the heating system with price increase per year 3 % (a) building A-1; b) building B.

Fig. 9a and 9b depict the results of the full cost calculations at a total energy price increase per year of 6 % in building A-1 (Fig. 9a) and building B (Fig. 9b). It can be observed that also with the increased energy price rate per year, the PV supported heating systems are clearly cheaper.



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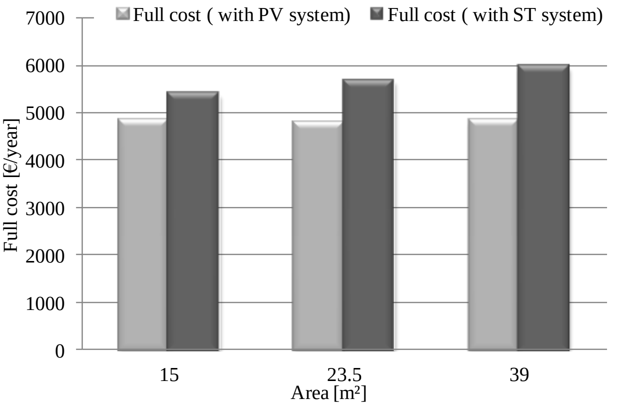

b)

Fig. 9. Full cost of the heating system with energy increase per year 6 % (a) building A-1; b) building B).

Variation of investment costs

In order to evaluate the influence of the assumptions of the investment cost of the solar support systems on the full cost calculations, the cost assumptions have been varied in a range of ± 25 % of the price assumptions in Table 3. Fig. 10 shows the resulting full costs with error bars in dependence of investment cost variations of ± 25 %. It can be seen that with these variations the full costs for PV-based solar support systems clearly remain lower than those of the investigated solar thermal-based systems.

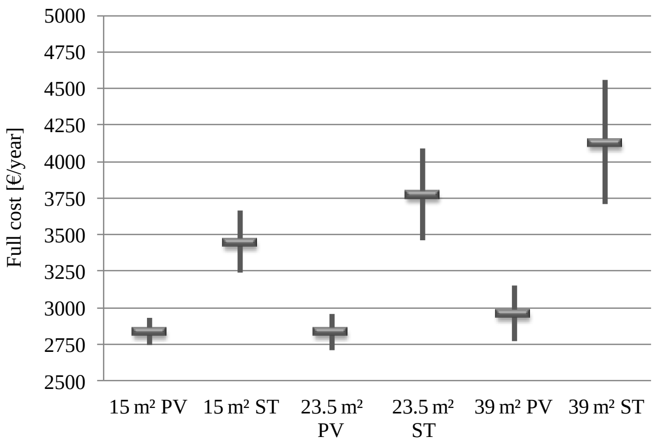

Fig. 10. Full costs with error bars in dependence of the price assumptions ± 25 % variation (simulation results for building A-1, price increase rate 3 %).

Fixed amount of investment funds (combination of PV and ST)

The basis of this comparison is the limitation to a fixed amount of investment funds. Those funds are used to tailor different possible system combinations to achieve solar support for the heating system of the buildings. In Table 6 differently dimensioned combinations are listed.

TABLE 6
INVESTMENT COST ASSUMPTIONS

Type of system	Details	Investment cost [€]
System 1 (only solar thermal collector field, total solar area 15 m²)	15 m² ST + 1 m³ hot water storage	10,660
System 2 (only PV panels, total solar area 39 m²)	5.5 kWp PV + 0.56 m³ hot water storage	10,850
System 3 (50 % ST and 50% PV, total solar area 23.5 m²)	5 m² ST + 2.6 kWp PV + 0.56 m³ hot water storage	10,520
System 4 (70 % PV and 30% ST, total solar area 26 m²)	2.5 m² ST + 3.3 kWp PV + 0.56 m³ hot water storage	10,260

Fig. 11 shows primary energy consumption, CO_2 emissions and full costs of the four systems.

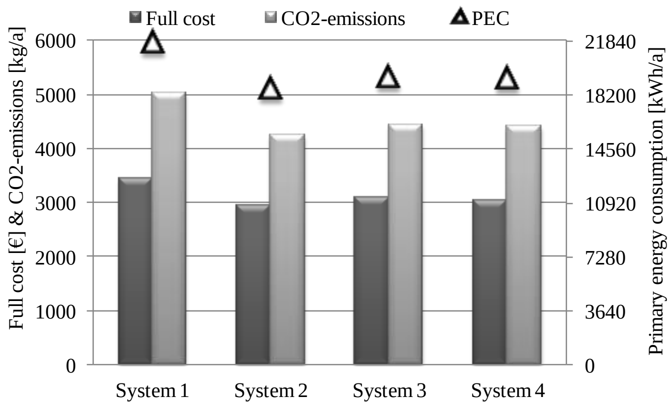

Fig. 11. Full costs, primary energy consumption and CO_2 emissions for the four proposed systems (building A-1, price increase rate 3 %, primary energy factor electricity 2.6).

System 2 (only PV) gives the lowest primary energy consumption and full costs, whereas system 1 (solar thermal only) gives the highest costs and primary energy consumption. The differences between the systems 2-4 are very small, so combinations between PV and solar thermal yield nearly the same results as the PV only option.

VI. SUMMARY AND OUTLOOK

In this study, two different solar support strategies for heating systems based on different collector technologies (PV and solar thermal) have been evaluated. Two different building heating demands and two electricity household demands have been taken into account for one given building in Germany, thereby creating different combinations to make up for heating and electrical load. The building demands which were taken into account represent buildings with relatively low heating demands. Different solar collector field areas, electrical primary energy factors and investment costs were taken into account in the calculations.

The results for the primary energy consumption (the same area for PV and solar thermal presumed) show a strong dependency of the results on the relation between heating demand and the electrical household demand and on the primary energy factors assumed. A general statement if solar thermal or PV supported heating systems lead to lower primary energy consumption cannot be made.

The cost comparisons show a clear advantage of the PV based solar support solutions over the solar thermal based solutions. This is caused, firstly, by the lower investment costs for PV panels to date compared to solar thermal collectors and, secondly, by the price difference between electricity and gas (the PV based solution covers beside a part of the gas demand also a part of the electrical household demand, whereas the solar thermal solution only covers a part of the gas demand (in higher magnitude)).

Exemplary cases have been evaluated, made out of combinations of components at fixed total investment funds, making up for the solar support of the heating system together.

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