Conference Proceedings

EuroSun 2016
Palma de Mallorca (Spain), 11 – 14 October 2016

Energetic and economic comparison of different energy concepts based on solar energy for residential buildings

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Abstract

This paper investigates the benefit of the combination of solar thermal systems and photovoltaic systems for residential buildings. In this study, different solar energy supply concepts were modelled in the Matlab/Simulink toolbox CARNOT. The simulations were conducted with changing ratios of installed solar thermal and photovoltaic surface. Each concept was equipped with an optional battery storage. The results indicate an advantage of a combination of both solar systems with respect to the percentage of self-consumption. Economically, solar thermal plants affect the investment costs adversely because of higher unit prices compared to PV modules. Nonetheless, a combination of both systems is useful for some concepts.

Keywords: *solar thermal, photovoltaic, residential building, energy concept;*

1. Introduction

The EU guideline EPBD (Energy Performance of Building Directive), which came into effect in 2010, requires stricter building standards for new construction. To comply with this directive, all new buildings from 01.01.2021 onwards must fulfill at least the “nearly zero-energy building”-standard (European Union, 2010). For this purpose, the majority of the energy demand must be provided by renewable energies. The resulting significantly lower heat demand, however, means that the current demand ratio for thermal and electrical energy in residential buildings will change. Until now, electricity has only represented 16 % of the energy consumption in German households while 84 % was used for thermal purposes, in which room heating required 69 % and domestic hot water 15 % (Deutsche Energie-Agentur, 2015). As a result of this lower heating demand, the ratio between requirements for room heating and domestic hot water will also converge until they are almost balanced. Accordingly, greater priority must also be given to the domestic hot water demand.

In new buildings photovoltaic systems are primarily used as a solar renewable energy. This is reinforced also by the fact that in recent years the investment costs for photovoltaic systems have declined (Wirth and Schneider, 2016). Solar thermal systems have not experienced such a steep learning curve and as a result the investment cost has remained constant. In addition, the economy of PV systems is easier to identify. The energy production depends only on the irradiation and, in contrast to solar thermal systems, is not user related. The generated and fed energy is remunerated with a fixed sum. The federal government implemented a “flexible ceiling” for these feed-in tariffs which makes it more difficult to operate grid-connected PV systems economically. One key to more economical operation is self-consumption. In 2012, grid parity was reached as a consequence of the steady reduction of the feed-in remuneration and the increase of electricity prices for households (Quaschning et al., 2012). This was the turning point where the use of generated PV power became more cost-effective then the consumption of grid electricity. This development leads to new options for the use of photovoltaic energy in single-family homes. Covering the heat demand with electric energy becomes an interesting opportunity for increasing self-consumption. One possibility is to combine photovoltaic systems

doi:10.18086/eurosun.2016.04.02 Available at http://proceedings.ises.org

with heat pumps in order to cover the heat demand of single-family houses. As a result, heat generation with PV competes with other heat generation systems, in particular with solar thermal systems. The objective of this paper is to analyze this competition between and evaluate the combination of solar electric and solar thermal systems in residential buildings.

2. Methodology

The presented studies were performed in Matlab/Simulink (The MathWorks Inc., 2016). In addition, the expansion Blockset CARNOT (Conventional And Renewable Energy System Optimization Blockset) was used (Hafner et al., 1999). CARNOT contains predefined Simulink blocks from the fields of building and supply technology and has been conceived to perform detailed simulations and analyses in building energy supply.

2.1. Concepts

Four different concepts are implemented in Matlab/Simulink with different backup-heating systems. First, with a fossil fuel-boiler and a biomass-boiler, two systems are applied which operate independently from the electrical grid. Furthermore, two concepts based on power-to-heat (p2h) are part of the investigation: an electrical heating rod and a heat pump.

Due to the focus on solar energy supply, both photovoltaic and solar thermal systems were considered in each model. Based on the simulation model, a 50 m² roof was analyzed for the use of either solar thermal collectors, PV modules, or a combination of both. The ratio of installed PV modules and solar thermal collectors is varied in steps of 10 m². The results were then compared to the pure use of each solar technology, i.e. only solar thermal collectors or PV modules. In addition, the influence of energy storage for each concept was investigated. The capacity of the electrical as well as thermal storage was adjusted according to system sizes. For each kW_{peak} of installed photovoltaic power, a battery capacity of 1 kWh is used. The thermal storage has a defined basic volume of 250 l, which increases by 500 l per 10 m^2 solar thermal collector.

2.2 Database and control parameters

Meteorological data are an important aspect for solar energy simulations. Especially for photovoltaic and solar thermal systems, a temporally high resolution of the weather data is desired. For this investigation the climate data of Ingolstadt, Germany are used. The data were generated with the software Meteonorm (Meteonorm, 2016). The weather data set has to be adapted and extended for use in CARNOT. After this modification, the data now includes relevant parameters such as the direct and diffuse radiation on a horizontal surface and also location-based parameters such as hour angle, zenith angle and declination angle of the sun.

The analysis is exclusively carried out for detached single-family houses. Within the IEA-SHC Task 44, reference buildings were defined for the simulation setting which ensure the same conditions for all simulations to allow for comparison between investigated concepts (Dott et al., 2013). These buildings do not differ in geometry but solely in their U-values for the walls and therefore building types with different energy standards arise. Three building types are further defined: SFH15, SFH45 and SFH100. SFH stands for Single Family House and the additives 15, 45 and 100 indicate the specific heating demand in kWh/(m²*a). SFH15 represents a building envelope with very high energy efficiency, SFH45 represents current legal requirements or a renovated building with a building envelope of good thermal quality, and SFH100 represents a non-renovated existing building (Dott et al., 2013). Because of the higher heat demand, the SH100 building type requires radiator heating. All other boundary conditions (weather data, building orientation, roof slope and orientation) of the simulation remain the same. The building is oriented south and the roof pitch is 45°.

The thermal load of the building arises from the building parameters in the model and the weather conditions. The domestic hot water tapping profile is generated according the VDI-guideline 4655 (reference load profiles of single-family and multi-family houses for the use of CHP systems). The guideline includes standardized load profiles for 10 typical days for 15 different climate regions. These typical days differ depending on the day of the week, the temperature and the cloudiness. The average daily temperature determines whether it is a summer, winter, or a transition day. Regarding the cloudiness, a fine and a cloudy day can be distinguished. A combination of all possibilities would yield 12 typical days, but no distinction is made according to the cloudiness of the summer typical days. Public holidays are treated like Sundays. To determine the public holidays, 2015 is chosen as the reference year. Using the meteorological data, profiles for the annual simulation are generated. Based on the guideline, which provides a domestic hot water demand of 500 kWh/person/a, results for the assumed 4-person household indicate an annual hot water demand of 2,000 kWh/a. The electrical load profile can be generated in a similar fashion. Contrary to the assumption of 1,750 kWh/person/a, a value of 1,000 kWh/person/a is assumed here. Especially in newer buildings, much more efficient components are installed. This leads to annual electricity consumption of 4,000 kWh/a for a 4-person household.

For the reference building in the IEA Task 44, a room temperature of 20°C is set, wherein a hysteresis of ± 0.5°C is set for activation of the heating circuit. The inlet temperature is regulated depending on the outside temperature. The maximum value for floor heating is 35°C and for radiator heating 55°C. The domestic hot water is mixed to a temperature of 45°C. The inflowing cold water, used for mixing, has a constant temperature of 10°C. The combined thermal storage tank is divided into two areas. The upper part is kept in a temperature range between 48°C and 52°C (SFH15 and SFH45). For the SFH100 this area is heated up 62°C. During the winter months, the lower part of the thermal storage is kept at a minimum temperature of 35°C in the case of floor heating. In case of radiator heating, this part is reserved for the solar thermal system. The loading of the upper part has thereby priority within the control. The biomass-powered boiler differs from fossil-fueled boiler with regard to start-up and switch-off times. Due to the somewhat sluggish overall system, the system is booted up slowly when reaching the lower threshold value and accordingly the power is lowered already slowly just before the maximum permissible temperature.

3. Energetic evaluation

The simulation results are evaluated in terms of energy coverage. The electrical coverage for the PV-system is the PV generation E_{PV} less the feed-in energy $E_{\mathrm{PV,feed\text{-}in}}$ relative to the total energy consumption $E_{\mathrm{el,total}}$.

$$C_{\mathrm{el}} = \frac{E_{\mathrm{PV}} - E_{\mathrm{PV,feed\_in}}}{E_{\mathrm{el,total}}} \qquad \text{(eq. 1)}$$

The total energy demand results from the household electricity demand $E_{\mathrm{el,HH}}$ and the electrical demand for heating $E_{\mathrm{el,heat}}$.

$$E_{\mathrm{el,total}} = E_{\mathrm{el,HH}} + E_{\mathrm{el,heat}} \qquad \text{(eq. 2)}$$

For the solar thermal system the thermal coverage can be determined in a similar manner by setting the thermal energy generated by the solar thermal system E_{ST} in a relation to the total thermal energy demand $E_{\mathrm{therm,total}}$.

$$C_{\mathrm{therm}} = \frac{E_{ST}}{E_{\mathrm{therm,total}}} \qquad \text{(eq. 3)}$$

The total energy demand is calculated from the sum of energy for domestic hot water $E_{\mathrm{therm,dhw}}$, the demand for space heating $E_{\mathrm{therm,heat}}$ and the thermal losses $E_{\mathrm{therm,loss}}$.

$$E_{\mathrm{therm,total}} = E_{\mathrm{therm,dhw}} + E_{\mathrm{therm,heat}} + E_{\mathrm{therm,loss}} \qquad \text{(eq. 4)}$$

In addition, the electric self-consumption of the photovoltaic system is assessed. These are calculated similarly to coverage only that in this case, the used photovoltaic energy is set in a relation to the total generated power of the PV system.

$$SC_{\mathrm{el}} = \frac{E_{\mathrm{PV}} - E_{\mathrm{PV,feed\_in}}}{E_{\mathrm{PV,total}}} \qquad \text{(eq. 5)}$$

Tab. 1 shows the annual thermal electrical energy amounts results from the simulated systems and the predetermined load profiles. All other annual amounts vary with the collector area, because the run-times of the backup-systems depends on the energy generated from the solar thermal system.

Tab. 1: Annual energy amounts of the reference buildings SFH15, SFH45 and SFH100

	SFH15 Values in kWh/a	**SFH45** Values in kWh/a	**SFH100** Values in kWh/a
Annual electricity consumption			
household	4.090	4.090	4.090
Annual heating demand			
domestic hot water	2.100	2.100	2.100
space heating	3.100	8.010	21.200

If one calculates the specific heat demand for the simulated annual space heating demand and an assumed floor area of 140 m^2, one obtains the values 22 kWh/m2/a, 57 kWh/m2/a, and 152 kWh/m2/a. These values differ from the defined values 15 kWh/m2/a, 45 kWh/m2/a and 100 kWh/m2/a. This is mainly due to the different weather dataset for Ingolstadt. To determine the defined values the weather data set for Strasbourg was used. The annual average outdoor temperature is in Ingolstadt with 8.8°C below the temperature in Strasbourg with 11°C. The radiated energy on the 45° inclined surface is with 971 kWh/m2/a 20 % smaller than that of the referenced weather data set (1,227 kWh/m2/a). The designations are retained hereinafter.

3.1. Concepts without electrical energy storage

As already described in the methodology, different ratios of the installed photovoltaic modules to solar thermal panels are compared and evaluated. This examination is carried out for various concepts and building standards. Fig. 1 shows the result for the SFH15 building type. The electrical coverage is lower in systems with p2h combined with PV systems, because the total electrical consumption is higher. Due to the even higher electrical demand when using a heating rod, the electrical coverage is about 20 %, slightly below the heat pump (23 %). The electrical self-consumption percentage changes accordingly (34 % compared to 26 %). Due to the higher electrical energy demand, a higher self-consumption can be achieved with these two systems in comparison to the boiler systems.

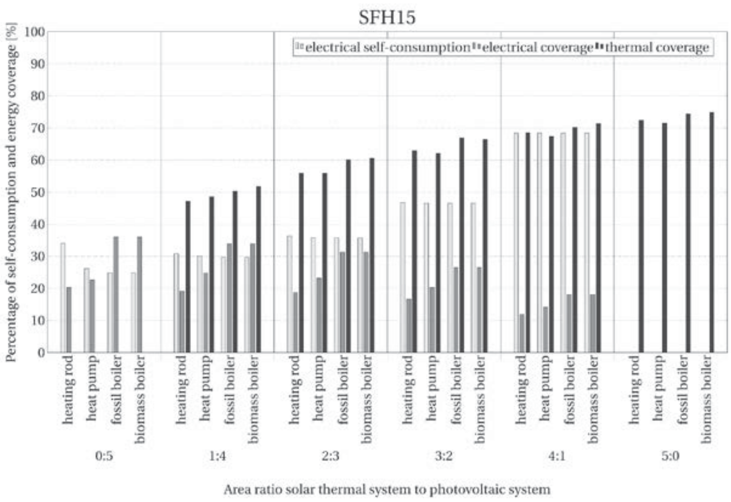

Fig. 1: Percentage coverage and self-consumption at different area ratio and backup systems for the building standard SFH15

Through the addition of a solar thermal system, lower operation time for the backup-systems is required. Moreover, the solar thermal system is now simultaneously active with the photovoltaic system and the produced photovoltaic power is used to cover the domestic electrical demand primarily. Thus, the electrical self-consumption of all concepts increases and the electrical coverage decreases. However, this is also due to the now-smaller photovoltaic surface. With this decrease, it is possible to consume a higher percentage of the generated energy. For the fossil fuel boiler and for the biomass boiler, the electrical characteristic values are the same, as they both operate independently of the power and only the domestic electricity demand is covered.

For the thermal coverage, a maximum value of 75 % can be achieved. If one increases the solar thermal surface from 30 m^2 to 50 m^2, the thermal coverage hardly changes. The heat demand of the SFH15 building is too low as the possible heat, generated by a 40 m^2 or 50 m^2 solar thermal system, can be used. The system is oversized and is therefore often in stagnation.

For the SFH45 building type, the results are similar to SFH15 (cf. Fig. 2). The electrical characteristic values for the fossil system and the biomass system remain unchanged by the independence of their power production. The heating demand of the SFH45 is higher, which results in a higher utilization of the heating system. With a heating rod or a heat-pump can thus be increased the self-consumption of the photovoltaic power. But this also means that the total power consumption of the building is higher and hence the electrical coverage decreases. Also the thermal coverage is lower than for the SFH15 because of this higher heat demand.

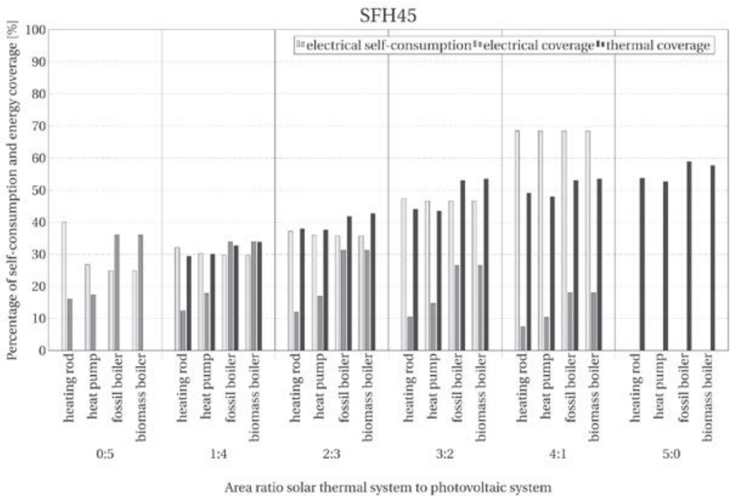

Fig. 2: Percentage coverage and self-consumption at different area ratio and backup systems for the building standard SFH45

When a vastly poorer building standard is considered (cf. Fig. 3), the results change once more. Here, the percentage of self-consumption with a photovoltaic-only system in combination with a heat pump is as high as with a heating rod. This is because heat pump operation and photovoltaic production occurs simultaneously more often due to the higher heat demand. The heat pump's higher electrical coverage of 15 %, compared to the heating rod with 8 %, is a result of the total energy demand as well as the electric energy demand of the heat pump, which is lower due to its coefficient of performance.

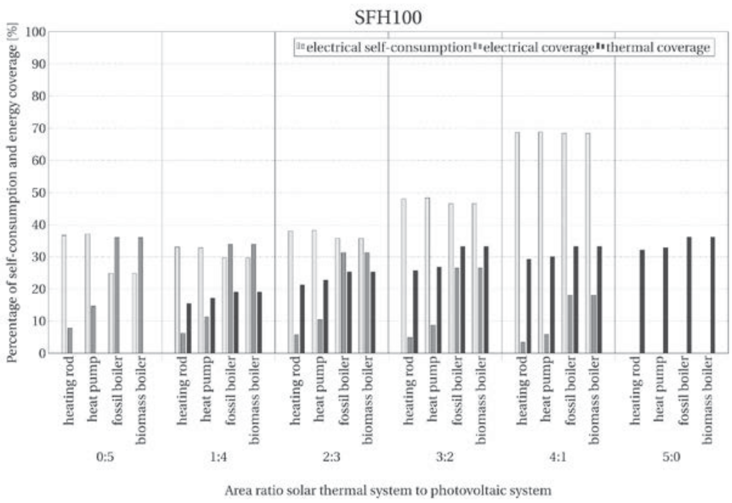

Fig. 3: Percentage coverage and self-consumption at different area ratio and backup systems for the building standard SFH100

This examination also shows that the electrical coverage of p2h-systems reacts similarly sensitive to the building standard as the solar thermal system. When the heat pump at a ratio of 3:2 is used as an example, the percentage of thermal coverage falls from 70 % (SFH15) to 53 % (SFH45) to 33 % (SFH100). In contrast, the percentage of electrical coverage drops from 20 % (SFH15) to 15 % (SFH45) to 9 % (SFH100). This corresponds to a deterioration of 55 % from building standard SFH15 to SFH100 for the electrical coverage and a decrease of 53 % for the thermal coverage. It is also seen that even for the SFH100, despite the increased heating demands little improvement of the thermal coverage can be achieved by increasing the solar thermal plant of 30 m² to 50 m².

3.2. Concepts with electrical energy storage

For the electrical characteristic values other results are obtained when an energy accumulator is integrated as a buffer for the electrical energy. Fig. 4 shows the simulation outcome for the SFH15. By the electrical storage, it is possible to achieve a balance between production and demand, thus a higher electrical self-consumption as well as a higher electrical coverage can be reached.

An electrical storage is beneficial for systems with heat pump technology and a photovoltaic system. It can be used a similar energy quantity with a heating rod as well as with a heat pump but due to the lower overall electrical energy demand of the heat pump the electrical coverage is higher. The influence of the electrical storage deceases with a reduction of the photovoltaic area. In combination with a 50 m^2 photovoltaic system a doubling of the self-consumption to the system without an electrical storage can be attained. Even the electrical coverage can be doubled with a battery storage and a large photovoltaic system. By contrast, increases in self-consumption for smaller photovoltaic systems are lower, for example about ten percentage points (20 m^2 photovoltaic system) or about four percentage points (10 m^2 photovoltaic system) with a heating rod, as this represents an increase of about 37 % and 25 %. The rise in electrical self-consumption is less, too. An electrical storage results not in a change of the thermal characteristic values.

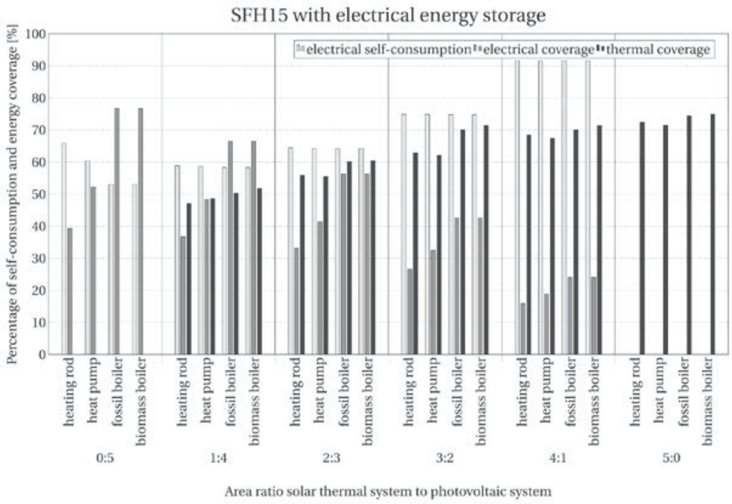

Fig. 4: Percentage coverage and self-consumption at different area ratio and backup systems for the building standard SFH15 and a battery storage

Owing to the higher thermal energy demand of the SFH45 the situation is somewhat different here (cf. Fig. 5). Although the battery storage maximum leads to a doubling of the electrical self-consumption, only lower electrical coverage can be accomplished here by the use of a heating rod or a heat pump, even though the electrical self-consumption remains almost the same. Again, the reason is the higher total energy demand of the building with poorer energy standard, which also has the consequence that a lower thermal coverage by solar thermal system is possible. The values for boiler systems, however, are again independent of the building standard.

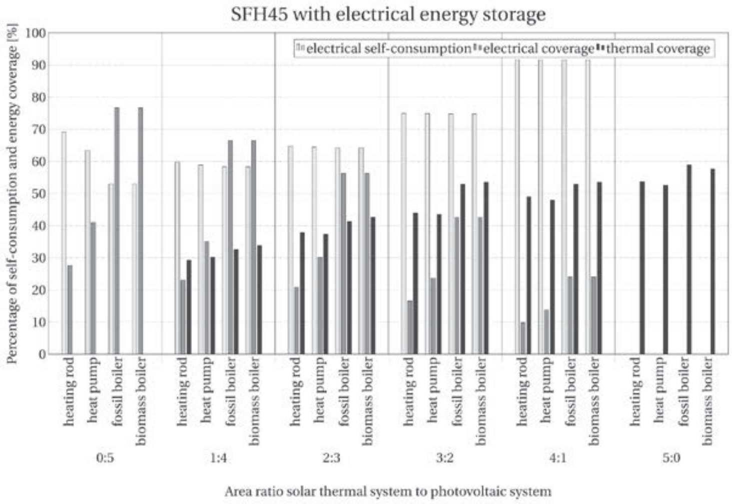

Fig. 5: Percentage coverage and self-consumption at different area ratio and backup systems for the building standard SFH45 and a battery storage

The same can be observed for the SFH100, whose results are shown in Fig. 6. Again approximately similar electrical self-consumption rates are achieved. However, the coverage ratio of the electrical energy at the total energy demand for electrical backup systems decreases.

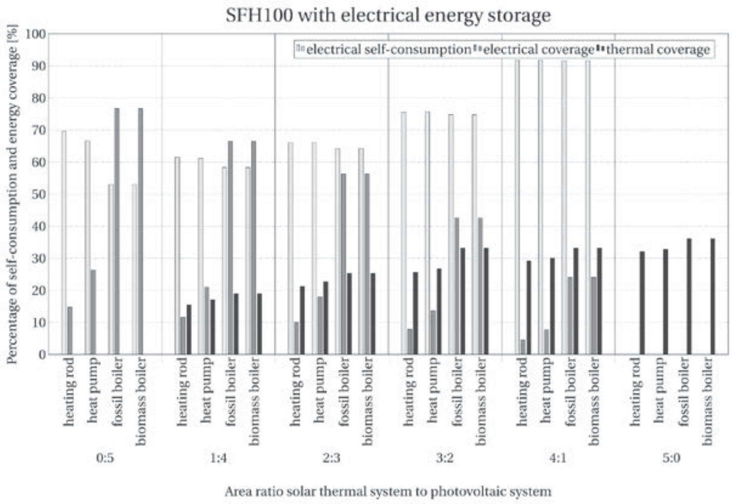

Fig. 6: Percentage coverage and self-consumption at different area ratio and backup systems for the building standard SFH100 and a battery storage

4. Economic evaluation

For the economic evaluation of the different concepts, the VDI-guideline 2067 is used. The method suggests summarizing the one-time investment costs and the ongoing payment during the period under consideration in equal annual payments, the so-called annuities. This approach allows a comparison of different system concepts. The annuity A_N of a system is calculated from the sum of the annuity of capital related costs, the annuity of needs related costs and operational related costs minus the annuity of the revenues (Lopez et al., 2011):

$$A_\mathrm{N} = (A_\mathrm{N,K} + A_\mathrm{N,V} + A_\mathrm{N,B}) - A_\mathrm{N,E} \qquad \text{(eq. 6)}$$

with: $A_{N,K}$ = annuity of capital related costs
$A_{N,\mathrm{V}}$ = annuity of needs related costs
$A_{N,\mathrm{B}}$ = annuity of operational related costs
$A_{N,\mathrm{E}}$ = annuity of the revenues (e.g. grid feed-in)

To calculate the annuities some assumptions regarding the observation period, the costing interest as well as rates of price change must be taken. The adopted actuarial mathematical parameters and assumptions about the energy are summarized in Tab. 2.

Tab. 2: Boundary conditions for the calculation of the profitability

Parameter	Value	Explanation/Reference
Observation period	20 years	VDI 2067
Interest rate	3 %	-
Price change	2 %	-
Electricity price	29.16 ct/kWh	BMWi, 2016
Gas price	7.06 ct/kWh	BMWi, 2016
Firewood price	4.46 ct/kWh	DEPV, 2016
Feed-in remuneration	12.31 ct/kWh	Bundesnetzagentur, 2016

The investment costs of the different components are shown in Tab. 3. The costs for the thermal components are based on the Viessmann pricelist 2016. For the components which are variable in size (e.g. solar thermal system, photovoltaic system and battery storage) cost functions are used.

Tab. 3: Investment costs for different area ratio

	0/50	10/40	20/30	30/20	40/10	50/0
Heating rod			400 €			
Heat pump			6,000 €			
Gas-boiler			5,000 €			
Pellet boiler			12,000 €			
Thermal Storage	1,000 €	1.400 €	2,000	2,500 €	3,000 €	3,600 €
Solar thermal system	--	3,000 €	6,000 €	9,000 €	12,000 €	15,000 €
Photovoltaic system	7,500 €	6,000 €	4,500 €	3,000 €	1,500 €	--
Battery storage (lead)	9,240 €	7,280 €	5,600 €	3,640 €	1,680 €	--

Tab. 4 shows the total investment cost of each considered energy concept. The heating rod with its low investment costs shows in particular an economical advantage while concepts with a solar thermal system and without a battery storage have the higher investment costs. The high price of the pellet boiler increases the investment costs for these concepts. A battery storage compensates the higher cost of solar thermal collectors compared to photovoltaic modules and there is, with regard to various area ratios, only a small difference in the investment costs.

Tab. 4: Investment costs of the considered energy systems with and without battery storage

	0/50	10/40	20/30	30/20	40/10	50/0
Systems without battery storage						
Heating rod	8,900 €	10,800 €	12,900 €	14,900 €	16,900 €	19,000 €
Heat pump	14,500 €	16,400 €	18,500 €	20,500 €	22,500 €	24,600 €
Gas-boiler	13,500 €	15,400 €	17,500 €	19,500 €	21,500 €	23,600 €
Pellet boiler	20,500 €	22,400 €	24,500 €	26,500 €	28,500 €	30,600 €
Systems with battery storage						
Heating rod	18,140 €	18,080 €	18,500 €	18,540 €	18,580 €	19,000 €
Heat pump	23,740 €	23,680 €	24,100 €	24,140 €	24,180 €	24,600 €
Gas-boiler	22,740 €	22,680 €	23,100 €	23,140 €	23,180 €	23,600 €
Pellet boiler	29,740 €	29,680 €	30,100 €	30,140 €	30,180 €	30,600 €

4.1. Concepts without electrical energy storage

Contrary to the investment costs the system with gas-boiler has the lowest degree of annuities (c.f. Tab. 5). One the one hand, this is due to the relatively low investment cost of the gas boiler and on the other hand it is mainly up to the currently low gas price. The high cost of a pellet-boiler means that this system has the highest annuities for buildings with low heating demand (SFH15). For SFH45 and SFH100 standard are the mains supply costs for the heating rod however so high, that this concept has the highest annuities. For concepts based on power-to-heat the area ratio of 10/40 has the lowest annuity for the building standard SFH15 and SFH45. Here, the higher investment costs of the solar thermal system is compensated by the less electricity purchases form the grid. That the annuities of these systems greatly depend on the power consumption can be seen for example at SFH100 standard. There, the ratio of 20/30 has the lowest annuity because of the higher heating demand and therefore higher power consumption for thermal purposes.

Systems without thermal use of electricity have the lowest annuities by the ratio of 0/50 and increases with the enhancement of solar thermal collector area. These systems are also significantly more independent from the building standard. While here the annuities only rises between 10 %-20 %, these can double in power-to-heat-systems.

Tab. 5: Comparison of the total annuities of different concepts and building standards for various area ratios

	0/50	10/40	20/30	30/20	40/10	50/0
SFH15						
Heating rod	2,822 €/a	2,485 €/a	2,663 €/a	2,930 €/a	3,252 €/a	3,672 €/a
Heat pump	2,437 €/a	2,433 €/a	2,770 €/a	3,116 €/a	3,509 €/a	3,962 €/a
Gas-boiler	1,810 €/a	1,989 €/a	2,316 €/a	2,695 €/a	3,126 €/a	3,605 €/a
Pellet boiler	3,111 €/a	3,365 €/a	3,717 €/a	4,110 €/a	4,537 €/a	5,037 €/a
SFH45						
Heating rod	4,462 €/a	4,040 €/a	4,114 €/a	4,308 €/a	4,567 €/a	4,894 €/a
Heat pump	3,243 €/a	3,209 €/a	3,483 €/a	3,817 €/a	4,184 €/a	4,578 €/a
Gas-boiler	2,153 €/a	2,302 €/a	2,608 €/a	3,018 €/a	3,376 €/a	3,821 €/a
Pellet boiler	3,317 €/a	3,561 €/a	3,898 €/a	4,280 €/a	4,701 €/a	5,182 €/a
SFH100						
Heating rod	9,039 €/a	8,427 €/a	8,362 €/a	8,444 €/a	8,615 €/a	8,891 €/a
Heat pump	5,143 €/a	5,147 €/a	5,407 €/a	5,711 €/a	6,071 €/a	6,492 €/a
Gas-boiler	2,919 €/a	3,081 €/a	3,380 €/a	3,738 €/a	4,135 €/a	4,601 €/a
Pellet boiler	3,821 €/a	4,062 €/a	4,389 €/a	4,766 €/a	5,180 €/a	5,658 €/a

4.2. Concepts with electrical energy storage

When a battery storage is taken into consideration, the overall result of the different concepts does not change (c.f. Tab. 6). The concept with a gas-boiler has still the lowest annuity and the concepts with the pellet-boiler (SFH15) and with the heating rod (SFH45 and SSFH100) correspondingly the highest. For large-scale photovoltaic-systems, the annuity raises significantly and decreases depending on the size, what is owed to high investment costs of the battery storage. Therefore, the annuity for the area ratio 50/0 remains unchanged. However, this means that the economically optimum ratio shifts to larger solar thermal systems when higher heating demand exists. Is the optimum ratio for SFH15 standard still at 10/40, so it is at 30/20 for SFH45 standard and even at 40/10 for SFH100 standard. The advantage of an increased self-consumption is equalized by the high costs of the battery storage. In addition, the self-consumption cannot be increased as high that the savings in grid-consumption recoup the investment costs of the electrical storage. Especially for buildings with lower energetic standard, the mains supply can only be reduced about approximately 10 %.

Accordingly, a battery storage in combination with a conventional regulation is from an economical perspective not worthwhile. Only when the investment costs continue to fall, or the service life will be improved, changes may arise. Another improvement could cause an intelligent control strategy which considers forecasts of production and demand.

Tab. 6: Comparison of the total annuities of different concepts with battery storage and building standards for various area ratios

	0/50	10/40	20/30	30/20	40/10	50/0
SFH15						
Heating rod	3,804 €/a	3,149 €/a	3,280 €/a	3,331 €/a	3,445 €/a	3,672 €/a
Heat pump	3,410 €/a	3,231 €/a	3,393 €/a	3,517 €/a	3,703 €/a	3,962 €/a
Gas-boiler	2,828 €/a	2,788 €/a	2,931 €/a	3,096 €/a	3,320 €/a	3,605 €/a
Pellet boiler	4,129 €/a	4,164 €/a	4,331 €/a	4,511 €/a	4,731 €/a	5,037 €/a
SFH45						
Heating rod	5,471 €/a	4,730 €/a	4,734 €/a	4,711 €/a	4,761 €/a	4,894 €/a
Heat pump	4,179 €/a	3,983 €/a	4,124 €/a	4,216 €/a	4,379 €/a	4,578 €/a
Gas-boiler	3,172 €/a	3,101 €/a	3,222 €/a	3,418 €/a	3,569 €/a	3,821 €/a
Pellet boiler	4,335 €/a	4,360 €/a	4,512 €/a	4,680 €/a	4,895 €/a	5,182 €/a
SFH100						
Heating rod	10,009 €/a	9,110 €/a	8,981 €/a	8,848 €/a	8,809 €/a	8,891 €/a
Heat pump	6,148 €/a	5,948 €/a	6,026 €/a	6,115 €/a	6,266 €/a	6,492 €/a
Gas-boiler	3,938 €/a	3,879 €/a	4,226 €/a	4,138 €/a	4,329 €/a	4,601 €/a
Pellet boiler	4,839 €/a	4,861 €/a	4,423 €/a	5,167 €/a	5,374 €/a	5,658 €/a

5. Conclusion

The simulation-based study reveals that in terms of energy consumption it is possible to increase the electrical self-consumption with electric heating systems. The higher total electric energy demand is decreasing the electrical coverage and it must be obtained more energy from the grid. When using a heat pump the electrical coverage is slightly higher due to the better efficiency. With the addition of solar thermal systems for these systems the electrical self-consumption declines because then simultaneously with the solar electric energy also solar thermal energy is available and thus the photovoltaic power can often be used only to cover the household´s electricity demand. The use of a battery storage has only impact on the photovoltaic system and therefore only on the characteristic values of the electrical components. These values can be improved by the electrical storage. It turns out, however, that simultaneity is a crucial factor which is not always made possible by the battery storage.

From an economic view the conventional concept with a gas-boiler is the best system. In addition to the lowest investment costs are the running costs very low due to current gas prices. The economic viability of power-to-heat systems depends on the photovoltaic plant. Only if a large proportion of the electrical demand is generated by the photovoltaic system, the purchase of a heat pump is worthwhile. Otherwise, the improved efficiency of the heat pump cannot offset the high electricity costs. An electrical storage is no advantage because the invest costs are too high and savings in power supply costs are also too low. The acquisition pays off only if the costs of the battery storage decline, the costs of electricity increase or the feed-in tariff decreases.

The presented results are based on a simple system control and occurring simultaneity. Therefore, the impact of an energy management system on the self-consumption, thermal and electrical coverage will be examined in a next step. For this purpose a prediction of the expected production and load are included in the regulation in order to optimize the runtimes of the backup system.

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