Techno-Economical Optimization of Solar Energy Supply Concepts for Residential Buildings

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Abstract

The German energy transition must take place in the heat as well as in the power sector. In the field of solar energy, however, competition between solar-thermal systems and photovoltaic systems arises. A decreasing feed-in tariff leads to an increasing demand for solutions enabling self-consumption of energy. As a result, traditional heat generation systems, both fossil (e.g. gas heating boiler) and renewable (e.g. solar-thermal), enter a competition with systems being able to couple the electricity with the heat sector (e.g. photovoltaic + heat pump). The objective of this contribution is to analyze this competition and to evaluate the combination of solar-electric and solar-thermal systems in residential buildings. For this purpose, a linear optimization model is used. It also turns out that above all the investment costs for solar-thermal systems must fall, but also costs for battery storages are still too high. Only if several factors change, a combination of solar-thermal energy and photovoltaics becomes interesting from an economic point of view. For a reduction in emissions, the solar-thermal system competes with battery storage.

Keywords: solar systems, residential application, mathematical optimization, cost optimal

1. Introduction

The Paris climate agreement limits global warming to less than 2 °C, ideally less than 1.5 °C. To achieve this, a complete decarbonization is necessary by 2040 (Quaschning, 2016). Therefore, the share of renewable energy sources (RES) must be increased by a factor of 4 to 5 with respect to present values. In Germany, the implementation of RES primarily takes place in the electricity sector. This can mainly be determined by the coverage ratio. In 2016, the percentage of RES in electricity consumption was 32 % (Umweltbundesamt, 2017), while in final energy consumption it was only 12.6 % (BMWi, 2017). The integration of RES in the electricity system gets more and more difficult. Thus, the cost of redispatch in 2015 was 402.5 million euros (BDEW, 2017), because RES (predominantly wind power) had to be shut down in the north while conventional power plants had to be restarted in the south. This is due to grid bottlenecks, which do not permit enough power transfer from north to south or vice versa. This example shows that also the market is not always able to use the electricity sensibly.

One possible solution for dealing which such bottlenecks in the electricity grid is to couple different energy sectors, allowing more local self-consumption of the locally energy produced. Nevertheless, the question remains which sectors are best suitable to be coupled. In addition to mechanical energy (39 %), a large proportion of energy consumption in the domestic sector is attributable to space heating (27 %) and hot water preparation (5 %) (BMWi, 2017). Hence, there is great potential for coupling the electricity system with these sectors. A total of 56 % of the final energy consumption is due to heating demand (Quaschning, 2016). Thereby, the energy supply is still strongly based on fossil fuels. The share of fossil fuels in space heating is 75.1 % and in domestic hot water, it is 66.4 %. Only 13.7 % (space heating) respectively 9.3 % (domestic hot water) are covered by RES. The remaining demands are covered by district heating (9 % space heating, 4.4 % domestic hot water) and electricity (2.2 % space heating, 19.9 % domestic hot water) (Quaschning, 2016). Dominating RES for space heating and domestic hot water is still biomass (11 %). Solar-thermal systems as well as heat pumps are still less important, as the cover ratio of both technologies is only 1 % in 2014. Economic aspects prevent a stronger expansion of solar-thermal as well as geothermal systems (Quaschning, 2016). On the long term, efficient heat pumps must largely take over the supply of space heating and domestic hot water preparation, also due to the possibility of coupling with the electricity sector. However, the use of electric heaters can lead to more than double the current electricity requirement in Germany of 648 TWh in 2016 by an additional requirement of 770 TWh. This would be the case, if only gas heat pumps were used and the gas produced through power-to-gas (Quaschning, 2016). This in turn shows that the energy transition must take place both in the heat and power sector.

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In the field of solar energy supply, however, solar-thermal energy competes with photovoltaic systems, which is also due to the coupling of photovoltaics and heat pumps. Another aspect is the grid parity. This is the turning point where the use of self-produced PV power is more cost-effective then the consumption of grid electricity. Therefore, covering the heat demand with electric energy will become an interesting opportunity to increase self-consumption. The aim of this investigation is to analyze, under which conditions it may be useful to use a combination of solar-thermal and photovoltaic system and how the framework conditions would have to be changed, so that these systems can prove to be more cost-effective alternatives.

2. Simulation Model and Mathematical Description

To assess the research question stated above, the linear programming model urbs (lat.: city) (Dorfner and Hamacher, 2017) is used. The focus of the urbs model is to analyze urban energy systems. Amongst others, a low-carbon power system for Indonesia, Malaysia and Singapore was modelled (Stich et al., 2014). Currently, the model is used, in combination with the single-node variation of the model urbs, to optimize the energy supply of mixed use areas taking as example the Garching campus of TU Munich (Schweiger and Wedel, 2017). To answer the question concerning the competition of photovoltaic and solar-thermal systems, the original model, designed for the urban structures, was adapted to residential application.

2.1. Simulation Model

The urbs model (a mixed integer linear programming model (MILP)) is a simulation model for identifying cost-optimal system sizes and operation times for a portfolio of technologies and a given demand. The model consists of three main tuples[1], the commodities (*com*), the processes (*pro*) and the storages (*sto*). The commodities describe the different energy demands and external energy sources. Tab. 1 lists the implemented commodities.

Tab. 1: Different commodities implemented in urbs

commodity	***com***	**description**
Solar energy	solar	solar irradiation
Electricity	elec	electricity demand of the building
Heat	heat	heat demand of the building
Gas	gas	natural gas from the gas supply
CO_2	CO2	CO_2-emissions of the processes
Elec-buy	buy	electricity bought from the grid
Elec-sell	sell	electricity fed into the grid

With processes, it is possible to convert one commodity into another (e.g. electricity to heat by utilizing the process “heat pump”, cf. Tab. 2). These processes are defined by various parameters, e.g. input and output ratios, investment costs or the required roof area for solar energy systems. Tab. 2 shows the different investigated processes.

Tab. 2: Portfolio of processes in urbs

Process	***pro***	***com_in***		***com_out***
photovoltaic system	photovoltaic	solar	→	elec
solar-thermal system	solar-thermal	solar	→	heat
gas boiler	gas boiler	gas	→	heat
heat pump	heatpump	elec	→	heat
heating rod	rod	elec	→	heat
mini CHP	CHP	gas	→ →	elec heat
electrical grid	purchase feed-in	buy elec	→ →	elec sell

The last tuple, the storages, allows the time shift of different forms of energies and commodities. For residential buildings, there is a battery storage and a thermal energy storage (cf. Tab. 3).

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[1] Ordered list of elements

Tab. 3: Considered storage types

storage	*sto*	description
Battery	elec	battery storage
Tank	heat	thermal energy storage

Fig. 1 shows the basic structure and layers of the urbs model. A detailed description of the individual parameters is given in the following sections.

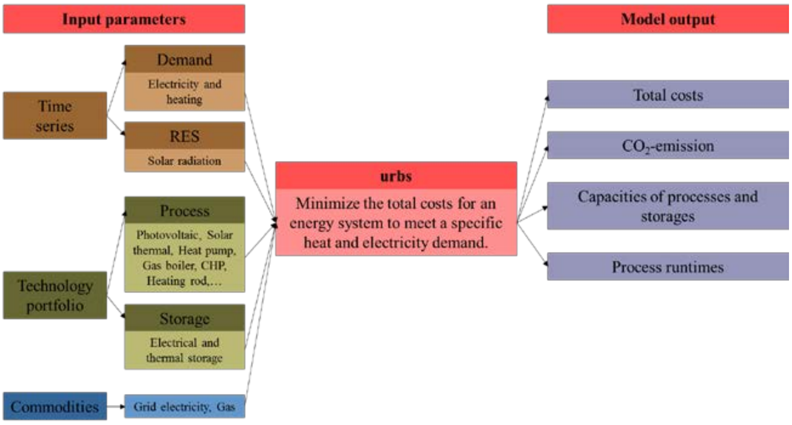

Fig. 1: Overview of the model urbs and the different components

2.2. Mathematical Formulation

The main aim of the model urbs is to minimize the total costs (c) for an energy system to meet a specific heat and electricity demand. These costs are composed of the investment costs $c_{pro,sto}^{invest}$, the variable costs $c_{pro,sto}^{var}$ (related to the operation of the system), the fixed costs $c_{pro,sto}^{fix}$ (independent from the operation of the system), the fuel costs $c_{pro,sto}^{fuel}$, the purchase costs $c_{pro,sto}^{purchase}$ (electricity costs), the startup costs $c_{pro,sto}^{startup}$ and the income from the feed-in $c_{pro,sto}^{revenue}$ for each process (*pro*) and storage (*sto*):

$$\min c = \min \sum_{pro,sto} [c_{pro,sto}^{invest} + c_{pro,sto}^{var} + c_{pro,sto}^{fix} + c_{pro,sto}^{fuel} + c_{pro,sto}^{purchase} + c_{pro,sto}^{startup} - c_{pro,sto}^{revenue}] \qquad \text{(eq.1)}$$

(Dorfner and Hamacher, 2017) provide a detailed description of the objective function and the constraints. The essential constraint is that the power from processes (*pro*), storages (*sto*) and the electrical grid (*grid*) has to meet the thermal (d_{therm}) and electrical (d_{elec}) demand for every time step (t):

$$\sum_{pro} p_{pro,elec}(t) + \sum_{sto} p_{sto,elec}(t) + grid(t) \geq d_{elec}(t) \qquad \text{(eq.2)}$$

$$\sum_{pro} p_{pro,therm}(t) + \sum_{sto} p_{sto,therm}(t) \geq d_{therm}(t) \qquad \text{(eq.3)}$$

To use urbs for residential buildings means some changes. For urban structures, it is often possible to use several technologies, whereas in a residential building, besides solar-thermal systems, only one backup technology (e.g. heat pump or gas boiler) is used. Therefore, the number of back-up processes ($num_{pro,backup}$) is limited to one:

$$\sum_{pro} num_{pro,backup} \leq 1 \qquad \text{(eq.4)}$$

The power demand and the power distribution in urban areas are much higher than in the domestic field. Hence, it is no problem to find the appropriate component sizes (cap_{pro}) on the market. For residential buildings, the necessary power would be partially below the power of available components, for example a heat pump with a thermal power less than 1 kW. Therefore, a minimum capacity ($cap_{pro,min}$) is defined, which the components must have at least:

$$cap_{pro} \geq cap_{pro,min} \qquad \text{(eq.5)}$$

The thermal load for room heating and for domestic hot water specifies the minimum power required for the backup system:

$$cap_{pro,backup} = d_{therm,max} \qquad \text{(eq.6)}$$

In addition, the step size of the possible extension of a process ($cap_{pro\text{-}new}$) is restricted, in other words, if the power is not sufficient, the next-largest component must be used. This is essential especially for the solar collectors, since here only the expansion by one collector is technically possible:

$$cap_{pro,new} \geq cap_{pro,new,min} \qquad \text{(eq.7)}$$

Since the solar energy is free of charge for an installed capacity, it can be economic to ‘destroy’ surplus energy using the storage efficiency. This is not possible in a residential building, especially for thermal energy. For this reason, the storage must not be charged and discharged at the same time. This can be prevented by considering additional variable costs for the storage systems. The costs also show that turn-off is associated with higher maintenance costs.

Nevertheless, it can be useful to control the power distribution of the solar energy systems, especially in case of a solar-thermal system. For this reason, a process shunt is implemented which enables the solar process to be deactivated and to analyze how much energy is not used. Fig. 2 shows a comparison of a simulation with (c.f. Fig. 1, upper diagram) and without (c.f. Fig. 1, lower diagram) the shunt process for the month of May. It is seen that part of the solar-thermal generation is not used for economic reasons (green area), leading to a reduction of the thermal storage from approx. 100 kWh to approx. 10 kWh. It can also be seen that only the energy of the solar-thermal system is ‘destroyed’.

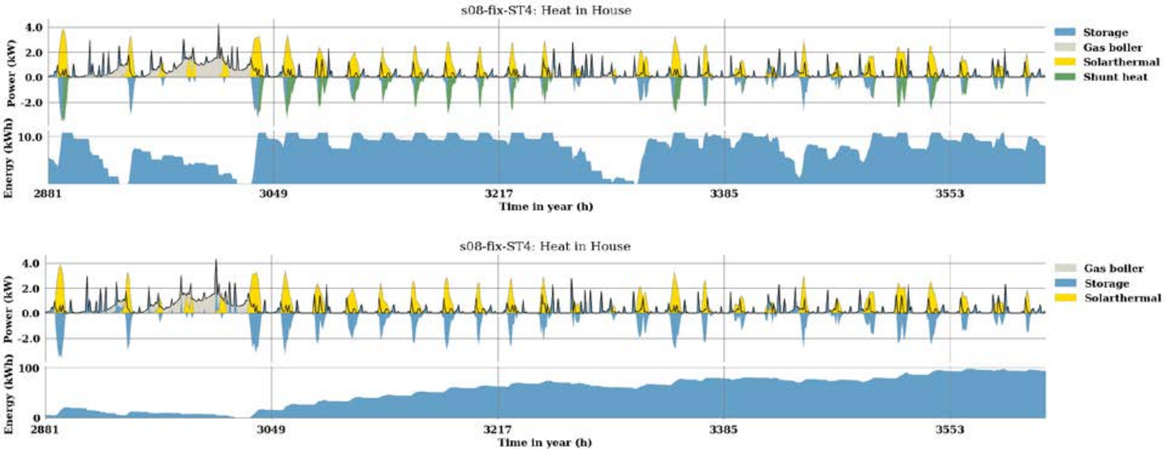

Fig. 2: Thermal energy flow with and without a shunt process for the month of May

3. Input Data

3.1. Technical and Economic Parameter

The different processes are defined with respect to their technical and economic parameters. The economic parameters are essentially the investment costs, the variable costs and the fixed costs. Added to this are the prices for the commodities/fuels.

The investment costs as well as the variable and fixed costs are stated in €/kW respectively €/kWh. Market surveys and data from scientific literature are used to determine the necessary investment costs. The costs of the solar-thermal system are composed of the costs for the flat-plate collector (320 €/m^2 (Sonne Wind & Wärme, 2017)), other component costs (90-160 €/m^2 (Kaltschmitt et al., 2014)) and installation costs (190 €/m^2 (Kaltschmitt et al., 2014)). This results in total system costs for the solar-thermal system of 620 €/m^2 (without storage). The specific solar yield for Germany is 425 kWh per square meter collector surface area (Eicker, 2012). By means of solar full-load hours, which amount to 1.140 h/a for the used weather data set (TRY Zone 13 (DWD, 2011)), the specific costs of the solar-thermal collector can be calculated (1,665 €/kW). The costs of photovoltaic systems are about 180 €/m^2 for the investigated sizes (5 m^2 -50 m^2), whereas a roof area of 8 m^2 is required for a capacity of 1 kW$_p$ (Solaranlagenportal, 2017). This results in costs of 1,440 €/kW$_p$ of the photovoltaic system. The cost of a thermal storage tank can vary between 1.50 €/l and 7.00 €/l (Kaltschmitt et al., 2014). This figures are in accordance with data available from an energy database, specifying an average cost of solar-thermal storages of 2.50€/l (Sonne Wind & Wärme, 2017). In addition, installation costs of 0.50 €/l are taken into account. The usable temperature spread is 65°C for the thermal storage. The prices of the batteries are currently changing very fast. In the second half of 2015, the system prices were already down to around 1,300 €/kWh with an annual average price reduction of 18 % (Hegner, 2017). For this reason, a price of 1,066 €/kWh$_{el}$ (a decrease of 18 % compared to the previous year) is assumed. The cost of the gas system is 600 €/kW$_{therm}$ (Kilburg, 2015), of the air/water heat pump 900 €/kW$_{therm}$ (Henning, 2012; Kilburg, 2015) and of the heating rod 75 €/kW$_{therm}$ (Fuhs, 2015). For the heating rod costs for the installation of 25 €/kW$_{therm}$ are added. The mini-CHP (combined heat and power) is the most expensive component with 6,430 €/kW$_{el}$ (ASUE e.V., 2014). Every process converts the related commodities with a certain degree of efficiency. The interest rate of all technologies is 3 %.

The variable costs of a photovoltaic system are near-zero (Dorfner, 2016). The solar energy system has variable costs due to the power of the solar pump, these electricity costs amount to 3-5 % of solar-thermal gains (Weyres-Borchert et al., 2015). The considered variable costs of the other systems are taken from (EIA, 2014) and range between 1.5 % and 8 %. The fixed costs are mainly maintenance costs, typically specified as a percentage of the investment costs (Verein Deutscher Ingenieure, 2012). The prices of the commodities/fuel are average prices for the year 2016 (BMWi, 2016). Tab. 4 summarizes the assumed cost parameters. The current feed-in tariff of photovoltaic electricity is 12.3 ct/kWh (Bundesnetzagentur, 2017). The remuneration of the CHP will change as a function of the electricity prices on the European Power Exchange. On average, it is about 11.8 ct/kWh (Verbraucherzentrale, 2015). This value differs only slightly from the feed-in tariff of the photovoltaic system, which is why only one tariff is used for this calculation.

Tab. 4: Cost parameters for the considered different technologies (depreciation period: 20 years)

Process	***com***	**Investment costs [€/kW]**	**Variable Costs [€/kWh]**	**Fixed Costs [%$_{inv}$]**	**Fuel Costs [€/kWh]**	**Efficiency**
photovoltaic system	solar	1,440	0	1,5	0	
solar-thermal system	solar	1,665	0.003	1,5	0	
gas boiler	gas	600	0.006	2	0.07	0.95
heat pump	elec	900	0.02	2	0.29	2.7 (COP)
heating rod	elec	100 €	0.005	3	0.29	0.99
mini CHP	gas	6,430 (elec)	0.5	8	0.07	0.23 elec 0.62 therm
Battery	elec	1,066	0.001	2		0.90
Tank	heat	30	0.001	2		0.92
Purchase	buy	0	0	0	0.29	
Feed-in	sell	0	0	0	-0.123	

3.2 Time Series

The time series are an essential part of the model. There are two possible types. On the one hand, the model requires time series for the demand. For the residential building, these are the electricity (d_{elec}) and thermal energy demand (d_{therm}). This energy demand must be covered by every simulation time step (t). On the other hand, since solar processes cannot provide a constant power due to irradiation, an intermittent supply for this commodity (*solar*) must be defined. In contrast to the demand curves, which indicate the actual demand in kWh/h, the intermittent supply curve is normalized to a value of 1.This is because the output of these processes depends on the installed capacity, which is variable in the simulation model.

The VDI guideline (Verein Deutscher Ingenieure, 2008) defines an electrical load profile as a function of the building location, the day of the weak, the ambient temperature and the cloudiness, which serves as the basis for the annual simulations. For a 4-person household, an annual electricity requirement of 4,000 kWh is assumed. The VDI guideline also defines the hot water tapping profile with an overall annual demand of 2,000 kWh. The heating energy demand as well as the yields of the solar-thermal system are generated by means of parametric models, requiring only a limited amount of parameters (Dittmar, 2004). Characteristic parameters such as areas, window sizes and opaque elements for the building model are taken from IEA-SHC Task 44. This publication defines reference buildings for use in simulations, ensuring a fair comparison of different technological concepts (Dott et al., 2013). The SFH45 building standard represents current legal requirements of a renovated building with a building envelope of good thermal quality, whereby SFH stands for **S**ingle **F**amily **H**ouse and 45 indicates the specific heating demand in kWh/m²a. With the used weather data set, the heat demand amounts to 8,000 kWh/a. The parameter model of the building is implemented in the simulation environment Matlab/Simulink and the additional CARNOT blockset (Hafner et al., 1999) to get the annual load curves as an input for the urbs model. In Simulink/CARNOT, a standard building, equipped with a boiler, a thermal storage and a solar-thermal system is implemented. The created load curves (Electricity and DHW) as well as the parameter model for the building are integrated in this model in order to get the necessary load curves for the subsequent linear optimization.

The annual simulation is used to get the necessary demand profiles for domestic hot water and space heating. Besides this, the simulation also enables to get the necessary input curves for the solar energy processes. The model urbs is a linear system. A large part of the examined components such as the photovoltaic system or the gas boiler can easily be linearly simulated and scaled. However, the solar-thermal system strongly depends on the ambient temperatures and supply temperature. In order to obtain a medium solar energy generation profile, simulations with 1-8 collectors were carried out in a Matlab/Simulink model. The area of a collector is 2.38 m^2. The storage size is adjusted according to the collector area and increased by 50 liters per square meter (Eicker, 2012). The volume flow is also increased linearly. Fig. 3. shows the annual yield of the various systems. The solar-thermal energy yields based on the number of collectors generally show logarithmic behavior. However, this behavior can be linearized for the collector areas as used in residential buildings (ca. 2–20 m^2). This is only possible for a small collector area, hence an extrapolation of the line leads to incorrect results.

In order to make a statement about the linear correlation, the Pearson correlation coefficient *r* and the coefficient of determination r^2 are calculated. With a correlation coefficient of 1, there is a completely linear coherence between the observed features. The correlation coefficient of the investigated systems is 0.988. The coefficient of determination is a quality measure for the linear adaption. The closer the coefficient of determination r^2 is to 1, the higher the probability of the linear coherence. Here the value is 0.976. These deviations are within the tolerance and a linearization and scaling of the solar-thermal system is possible without loss of accuracy. The normalized power curves of the 8 systems are averaged and act as input variables for the solar-thermal process.

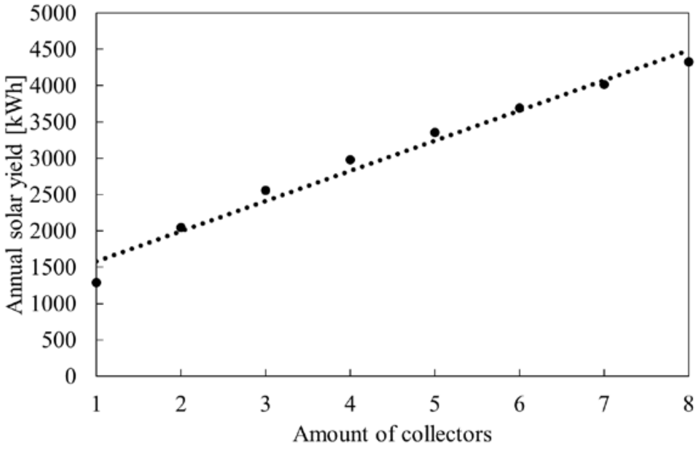

Fig. 3: Annual solar yields for 1-8 solar-thermal collector(s)

Fig. 4 shows a comparison of the solar-thermal performance for the parameter model in Matlab/Simulink and the linear model in urbs over a period of one week for two solar collectors. The results indicate that the generated solar-thermal power is nearly identical. The linear model produces a slightly higher peak load. However, the energy amounts are very low. The relative deviation between the CARNOT and the urbs model, as determined by eq. 8,

$$f = \frac{p_{CARNOT} - p_{urbs}}{p_{urbs}} * 100\ \% = \left(\frac{p_{CARNOT}}{p_{urbs}} - 1\right) * 100\ \% \qquad \text{(eq.8)}$$

is only 1.53 % for the solar-thermal power of an annual simulation. For the energy, the deviation is 0.17 % and thus even below one percent.

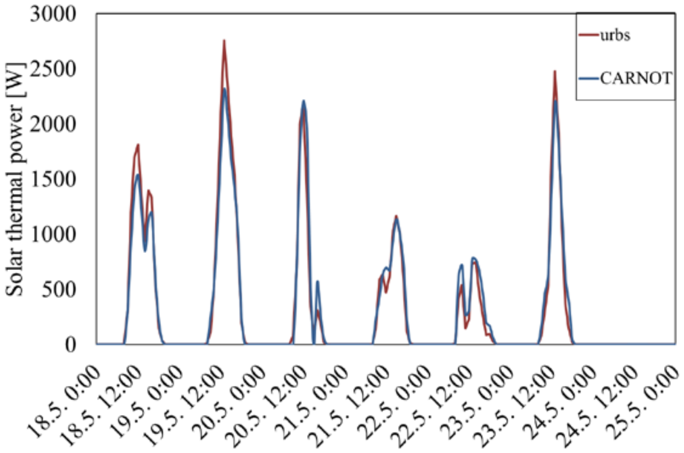

Fig. 4: Comparison of the generated solar power for the simulation models CARNOT and urbs

4. Scenario Results

This study is intended to show how solar-thermal and photovoltaic systems compete and under which conditions a joint use is economically reasonable. For that reason, various framework conditions are examined. On the one hand, the investment costs of individual technologies are modified and on the other hand, fuel prices and the remuneration are changed.

4.1. *Variation of the Investment Costs*

First, the study investigates the changes in system configurations for varying investment costs for the different processes. The investment costs for photovoltaic systems have declined in recent years (Wirth and Schneider, 2017). For this reason, one investigated scenario assumes drastically decreased investment costs of 50 % compared to today´s costs (s02). Solar-thermal systems have not experienced such a steep learning curve. Scenario s03 describes a potential cost reduction of solar-thermal systems by 50 %. A further scenario (s04) assumes even lower investment cost (75 % cost reduction compared to today`s cost level). The prices for batteries have also decreased in recent years. Similarly to the scenarios described above, a further cost reduction of 50 % compared to nowadays investment costs is assumed (s05). A technology that is currently too expensive for domestic applications is CHP. To make this technology competitive with the aforementioned, a cost reduction of 75 % is assumed (s06). Lastly, it is assumed that a solar-thermal system is already installed, on the one hand only for domestic hot water heating (2 solar collectors) (s07) and on the other hand for domestic hot water and space heating (4 solar collectors) (s08). All systems are compared with the base system as described before (s01).

Fig. 5 shows the results and the energy flows for the different investigated investment costs. The individual scenarios are listed vertically. This list shows the most cost-effective system for each scenario. Therefore, no comparison of the systems with one another is not possible. The annual costs for the different cost types are shown on the left. Revenue through feed-in is shown negative. The energy generation of the technologies used can be seen in the centre. Energy, which is not used by the building (feed-in, shunt process), is negative, too. This presentation allows a quick conclusion on how the system changes in the individual scenarios. On the right are the retrieved energies of the storages. It can be recognized, that the systems do not change with the investment costs. This is due to the low system costs for the gas boiler as well as the currently very low gas prices. The existing roof surface is completely covered with photovoltaic modules. If a solar-thermal system is already installed, a gas boiler is also used as the backup system. In this case, the thermal storage needs to be increased. However, because of the feed-in remuneration, this is economically more reasonable than buying a battery storage.

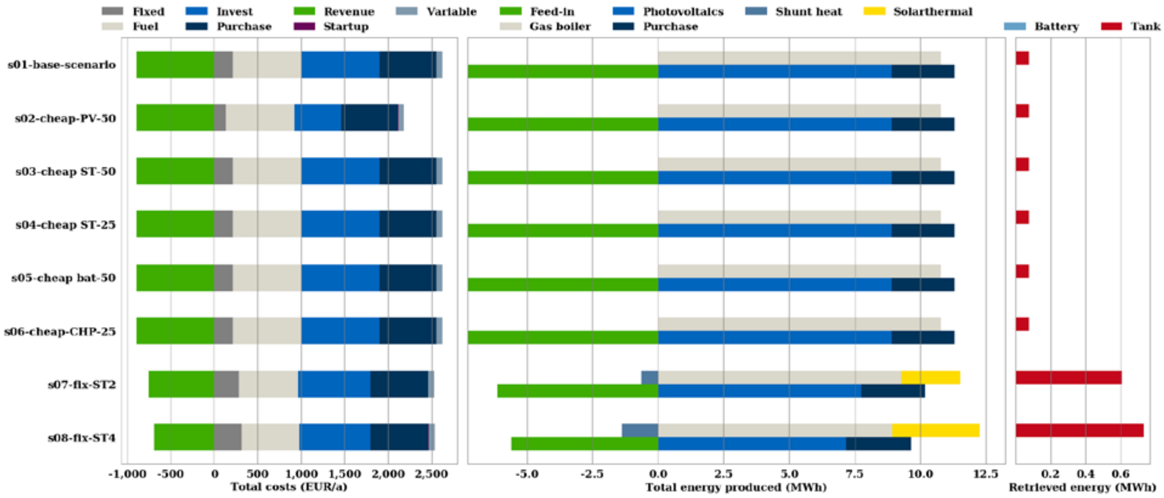

Fig. 5: Costs and energy flows for varying investment costs for the investigated systems

To account for a potential CO_2 tax, a CO_2-neutral energy demand of 15 % is assumed. This is in accordance with the requirements of the German Renewable Energies Heat Act (EEWärmeG). The different processes have a specific CO_2 emission per kWh. The basic system with gas boiler generates emissions of approx. 4,400 kg/a. The maximum annual CO_2 production is, therefore, limited to 3,750 kg.

Fig. 6 shows two essential findings. If there is no solar-thermal system, a battery storage must be installed to meet the emission limit. This reduces the emissions due to the purchase. At current prices, it is economically better to invest in a battery storage than in a solar-thermal system. Only in case of halved system costs, solar-thermal becomes competitive. A further cost reduction leads to the same result. In addition, the price of the battery storage does not affect the installed capacity.

The investigation with regard to the investment costs shows that these costs hardly affect the cost-optimal system configuration. Gas systems are the most economic at present prices. Only if CO_2 emissions are limited, some of the heat demand needs to be covered by the solar-thermal system. For this reason, the effect of the supply costs on the system is investigated, too.

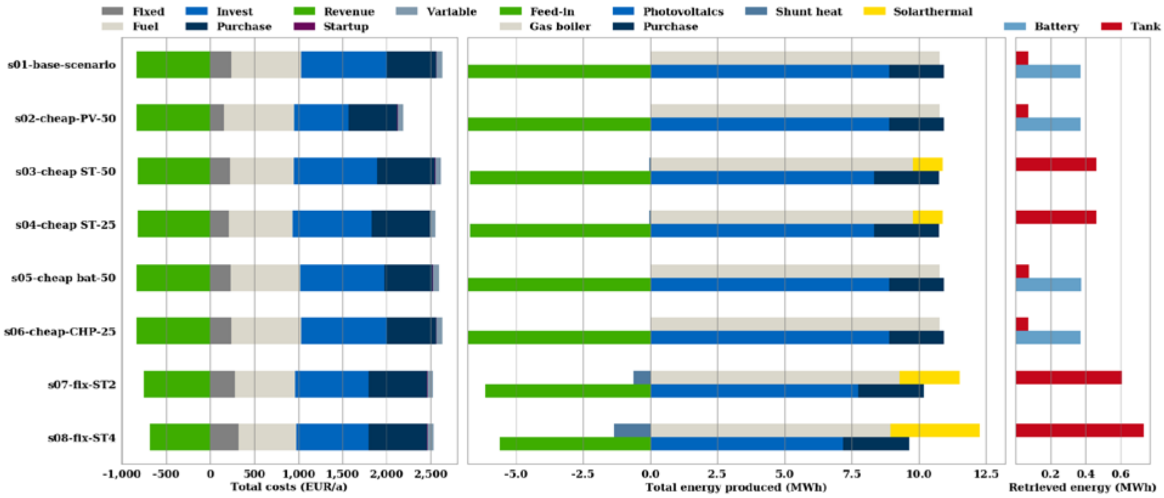

Fig. 6: Costs and energy flows for varying investment costs for the investigated systems and a CO_2 limit of 3,750 kg/a

4.2. Variation of Fuel Prices and Remuneration

In a further step, the energy supply costs and the remuneration are varied. In addition to an adjustment of the electricity costs with an increase (s09) as well as a decrease (s10) of 50 %, another gas price is also examined. The assumed gas prices represent a doubling (s11) and a tripling (s12) of current gas prices. This study also examines, what happens, when the remuneration is halved (s13) or when there is no longer any remuneration (s14).

Compared to the investment costs, it can be seen that the fuel prices have a much higher influence on the most economic system (cf. Fig. 7). A doubling of the electricity rate results in a battery storage being economically reasonable. If the electricity price is halved, the heat pump is more cost-effective than the gas boiler. This is also the case, if the gas price increases. For better economy of the heat pump, a doubling is already sufficient. Photovoltaic plants are economically unattractive with a reduction of the feed-in tariffs. The size is dimensioned in such a way that a high self-consumption can be reached. Thus, battery storages are again advantageous. The remaining roof area due to the small number of photovoltaic modules is, however, not used for a solar-thermal system.

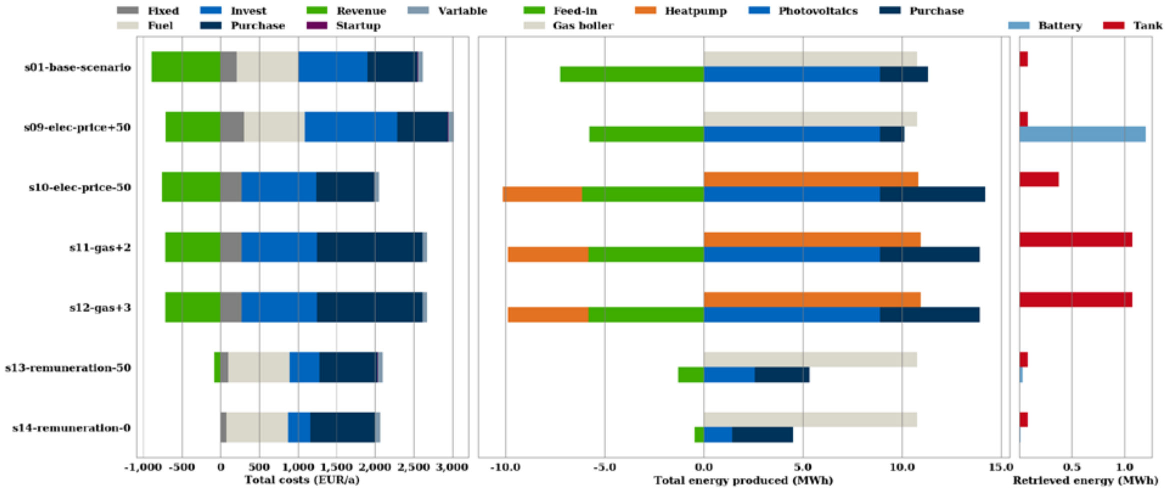

Fig. 7: Costs and energy flows for varying fuel prices and remuneration for the investigated systems

This shows that the decisive factor for a change in the energy systems is the price for the commodities. Investment costs have only a minor impact. A competition between photovoltaic system in combination with a heat pump and solar-thermal system cannot be observed. A reasonable combination of these three systems would require several boundary conditions to change at the same time.

5. Conclusions and Outlook

This study analyses the competition between photovoltaic and solar-thermal systems for residential applications. For this, the urbs model was adapted and extended for an application for single family houses. Due to the linearity of the model, it was shown that the yields of the solar-thermal system, which are strongly dependent on temperature, can be linearized with very high accuracy for the system sizes under investigation.

A major finding is that the cost-optimal system configuration is almost independent of the investment costs of the components. Gas-driven systems are currently the most economic ones. Only if the prices for electrical energy and gas vary, the system configuration changes. With a reduction in electricity prices as well as an increase in gas prices, the heat pump is more cost-effective than the gas system. An increase in the electricity price provokes an investment in a battery storage. A battery storage is also necessary if the CO_2 emissions are limited, whereby the size is independent of the investment costs. However, in the case of a reduction in the costs for solar-thermal systems, these are advantageous in comparison to the electrical storage. This shows that solar-thermal energy is an essential technology for decarbonisation.

However, there is no competition between photovoltaic and solar-thermal systems under current conditions. The combination of photovoltaic and heat pump is currently no more economic than a gas-driven system. This is due, on the one hand, to the feed-in tariff and, on the other, due to the currently low gas prices.

The aim of the study was to find the most economic system configuration for different boundary conditions. In this case, the solar-thermal system is disadvantageous compared to the photovoltaic system. However, not only economic optimization should be investigated. Further research must be conducted to answer how the different systems behave with different optimization objectives: (1) maximizing self-sufficiency, (2) maximizing self-consumption and (3) maximizing the use of solar energy. These questions will be addressed in further investigations.

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